ARMY SCIENCE BOARD

AD HOC STUDY ON

HUMAN ROBOT INTERFACE ISSUES

FINAL REPORT

SEPTEMBER 2002

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CONFLICT OF INTEREST

Conflicts of interest did not become apparent as a result of the Panel's recommendations.

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13. ABSTRACT (Maximum 200 words)

The Army Science Board Panel was tasked to: (1) Examine Army, DARPA, Navy, Air Force and NASA unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV) research and development efforts focused on human-machine interfaces, command and control of robots and supervisory control; (2) Project technologies and capabilities into the 2015-2020 timeframe and assess technology voids that may remain; (3) Determine the availability issues for applicable commercial systems and technologies; and (4) Propose cost-effective options or strategies for addressing identified technology voids.

The Panel's findings discuss the absence of a systematic study of human-robot interface design and a disconnect between end-users and the development process. The Panel's overall recommendations include: (1) development of an operational architecture with support from experimental data collected in operationally relevant scenarios in realistic environments; (2) Formulation of an FCS Block 1 human-robot interaction architecture consistent the FCS Operational Requirements Document in time for the FCS Milestone B decision; and (3) Establishment of a Science and Technology program aimed at developing a technical architecture for human robot interactions focused on autonomous ground robots.

14. SUBJECT TERMS

Robotics, technical architecture, operational architecture, human-robot interactions, autonomy, unmanned systems, human engineering

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Executive Summary

The Army transformation initiative, and the drive toward lighter, more lethal, and highly deployable formations, and the parallel evolution of the battlefield towards a dynamic, nonlinear, and highly dispersed environment, leads to one clear conclusion: intelligent unmanned systems will not just be required, but indeed will be critical to the success of our future forces. The defense community has recognized the value of even the first-generation fielded, unmanned systems. For example Predator, the unmanned aerial vehicle, proved its value as a sensor and weapons platform in battlefields as diverse as Bosnia and Afghanistan. This has led to a call for increased use of unmanned systems from the highest levels of our military establishment. President Bush stated at The Citadel on December 11, 2001 that

> "We're entering an era in which unmanned vehicles of all kinds will take on greater importance—in space, on land, in the air, and at sea."

Further the Department of Defense (DoD) 2003 budget submission quotes Secretary Donald Rumsfeld:

> "The growing use of unmanned aerial vehicles, the effective utilization of real-time intelligence, and the coordination among special operations and allied forces all demonstrate the cutting edge of what military transformation can achieve and offer a glimpse of a future transformed joint force."

The Army Science Board (ASB) has also recognized and acknowledged the value of unmanned systems in several recent studies focused on Army transformation, including the Summer Studies in 1999 and 2000. The clear recognition in these studies was that human elements of the force will require and use unmanned systems in ways that involve close interaction. Further, because the technology required for full autonomy will not be available in the abbreviated time frame for the initiation of Army transformation, efforts should focus on controlled, semiautonomous operations. These two observations lead naturally to the question of how humans and unmanned systems interact. In this study, we focused primarily on the issues surrounding the interactions of humans with unmanned ground systems. The ground environment presents significant challenges to autonomous systems, in large part due to the navigation requirements created by the wide variability of the terrain, and the close proximity between the autonomous entities and humans in the environment. These challenges to automated systems operation make the task of effective human-robot interactions particularly important to mission success. Further, airborne vehicles alone cannot efficiently perform a large number of tasks that are important to the Army necessitating the use of unmanned ground vehicles. However, the general conclusions we reached and the recommendations that follow are applicable to airborne systems as well.

During our study, the Human-Robot Interface panel and its government advisors either visited or were briefed on various science and technology programs within the Army, Air Force, Navy, National Aeronautics and Space Administration (NASA), and the Defense Advanced Projects Agency (DARPA). We examined these programs to identify the research and

development activities being carried out to allow effective interactions[1] between humans and (semi)autonomous systems, and to identify how effectively such systems were being transitioned into operational use.

Our key findings provide significant reasons for optimism as well as significant concern. First, we conclude that the technology for autonomous robotics has matured significantly. In particular, the Army Research Laboratory (ARL) lead robotics program, Demo III, has made significant progress in developing the perception technology essential to autonomous cross-country navigation. While much research and development remains, the progress made in the last 2 years (since the ASB last viewed the program) is remarkable. Nonetheless, we conclude that no existing programs systematically approach the challenges of interactions between humans and complex unmanned systems. Existing literature contains numerous examples that show that the lack of rigor in the design of interactions and interfaces between humans and complex systems can lead to catastrophic results (e.g., Three Mile Island, the USS Vincennes shoot-down of the Iran Air Airbus). If the human-robot interaction issue is not systematically addressed, we are concerned that similar catastrophic problems could arise in the application of robotic platforms in the Army. This, in turn, would result in severe setbacks to the induction of robotics into the force. Finally, we observed that no consolidated programmatic drivers are providing the “user pull” for semiautonomous and autonomous platforms that couple user needs directly with fundamental research. The 6.1, 6.2, 6.3, and 6.4 robotics communities are fragmented, with no single visible advocate or manager for these technologies in the Army. We are concerned that without such a driver, there is no motivation for hands-on experimentation with evolving unmanned systems. This in turn will restrict the development of effective interaction modalities, tactics, techniques, and procedures that will delay the induction of usable robotic entities into the force.

Our recommendations are divided into three parts. First, we recommend that the requirements community, led by TRADOC and the schools, establish an operational architecture for autonomous robots, and validate the architecture through an aggressive program of hands-on usage and experimentation with available robots in the field; (e.g., by the Army National Guard, by the Opposing Force (OPFOR) at the National Training Center). Second, we recommend the creation of a new systems-oriented program for the analysis, understanding, development, and improvement of human-robot interactions. We recommend that ARL, in cooperation with DARPA and other technology and system developers be the steward for such a program. This should facilitate technology insights and lessons learned from the field use of robots and the real time feedback establish the baseline for future developments; a process that should promote spiral development. Finally, we recommend that the Army insist that the Future Combat System (FCS) Block 1 program have, at a minimum, follower robots with a significant level of autonomy and surveillance and reconnaissance robots that can operate in limited environments—capabilities that can developed by maturing the technology that exists today.

[1] In this report, we use the terms *unmanned systems* and *robots* interchangeably. Further, we use the term *interface* and *interaction* interchangeably for reasons that are described later in the text.

1 TERMS OF REFERENCE

DEPARTMENT OF THE ARMY
OFFICE OF THE ASSISTANT SECRETARY OF THE ARMY
ACQUISITION LOGISTICS AND TECHNOLOGY
103 ARMY PENTAGON
WASHINGTON DC 20310-0103

REPLY TO
ATTENTION OF

14 MAY 2001

Mr. Michael Bayer
Chair, Army Science Board
2511 Jefferson Davis Highway, Suite 11500
Arlington, Virginia 22202

Dear Mr. Bayer:

I request that the Army Science Board (ASB) conduct a study on "Human-Robotic Interface Issues" as a means of addressing innovative methods for interacting with and controlling semi-automated, and fully automated systems on the battlefield. The study should address, but is not limited to, the Terms of Reference (TOR) described below. Appointed ASB members to this study are to consider the TOR as guidelines and may expand the study to issues considered important to the study. Modifications to the TOR must be addressed with the Chairman of the ASB.

Background:

a. The desire for rapidly deployable forces and the resultant drive towards lightweight mechanized fighting systems places a great premium on survivability by means other than heavy armor. An "ensemble" of manned and unmanned platforms operating cooperatively as an information-network-integrated team could provide the desired levels of survivability. In such a construct, the unmanned platforms could provide at least the following four functions:

(1) Serve as remote (potentially expendable) sensor assets that would support the situation awareness needed to keep the manned platforms out of harm's way.

(2) Semi-automated/fully automated platforms could serve as logistics resupply systems, reducing the number of manned platforms required on the battlefield.

(3) Unmanned platforms could provide communications relay capabilities, to ensure connectivity among dispersed forces.

(4) The scope of unmanned devices may extend to lethal applications, such as indirect fire support or a "robotic wingmen."

b. Depending on the role(s) that unmanned systems play on the battlefield, it is critical for soldiers to efficiently interact with and/or command and control such automated systems. This requirement raises a wide variety of issues ranging from the human factors of display systems, to cognitive models that represent context and shared awareness for collaborative manned/unmanned operations, to control devices that are used to manipulate the robots. Since technology for completely autonomous robots is unlikely until the 2020 timeframe, soldiers would have to either telephone operate the Unmanned Air Vehicle (UAVs) and Unmanned Ground Vehicle (UGVs), or perform supervisory control (i.e., the robots operate autonomously for routine parts of the mission and are telephone operated during critical mission phases).

TOR. The study should be guided by, but not limited to the following TOR:

(1) Examine Army, Defense Advanced Research Projects Agency, Navy, Air Force and National Aeronautical Space Administration UGV and UAV research & development efforts focused on human-machine interfaces, command and control of robots, and supervisory control.

(2) Project technologies and capabilities into the 2015-2020 timeframe, and assess technology voids that may remain.

(3) Determine the availability issues for applicable commercial systems and technologies.

(4) Propose (cost-effective) options or strategies for addressing any technology voids identified above.

Study Sponsorship. The sponsor for this study will be the Office of the Assistant Secretary of the Army, Acquisition, Logistics, and Technology.

Study Duration. The study shall be completed by November 2001.

Sincerely,

Kenneth J. Oscar
Acting Assistant Secretary of the Army
(Acquisition, Logistics and Technology)

2 INTRODUCTION

Study Sponsorship and Participants

SPONSOR: ASAALT

Task Force Members

Dr. Prasanna Mulgaonkar (Chair)
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Government Advisors
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ASB Secretariat Representative
MAJ Robert Grier

Other participants
Dr. Greg Canavan
Dr. Michael Krause

- Government advisors specifically selected to ensure:
  - Views from stakeholder DoD organizations carefully considered in study
  - Deliberations of panel coordinated with parent organizations

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Figure 1. Participants

Table 1. Meeting Schedule

Location	Program(s) Reviewed	Date	Study Panel Attendees
Washington DC	• Pat Eicker —Robotics Roadmap • Weatherington (OSD-ATL) —UAV • Deitchman (ONR)—Navy perspective	8/31/2001	Blair, Hofmann, Mulgaonkar, Dobbs, Mitchell, Krause, Perna
Ft Knox	• LTC Abbott —Battle Lab	9/27-9/28/01	Mulgaonkar, Dodd, Eicker, Blair, Perna, Hoffman, Martinez, Cheok, Dobbs, Mitchell
T. Indiantown Gap, PA	• ARL Demo III XUV demonstration	Week of 11/12/01	Blair, Mulgaonkar, Mitchell, Dobbs, Hoffmann, Taylor
Ft Leonard Wood – Maneuver Support Center	• Chem school • MP school • Mini-flail demo	11/15/01	Blair, Dodd, Eicker, Hofmann
Huntsville	• Ground robots • Software engineering • System simulation • Comm and others	11/29-30/01	Mulgaonkar, Dodd, Eicker, Blair, Perna, Hofmann, Martinez, Cheok, Dobbs, Mitchell
DARPA At SRI Arlington	• Scott Fish – Perceptor, UGCV • Doug Gage, Jean Scholtz – HRI • Alan Rudolph • Sam Wilson – MAV • Mike Leahy – UCAV • John Bay	12/14/01	Mulgaonkar, Dodd, Eicker, Blair, Mitchell, Hofmann, Dobbs
NIST	Jim Albus – robot architectures	12/14/01	Mulgaonkar, Dodd, Eicker, Blair, Mitchell, Hofmann, Dobbs
Natick Soldier Systems Center	Robotics for Objective Force Warrior Workshop	12/18-19/01	Blair, Eicker
SRI International	Greg Myers—human robot interface issues; speech recognition, CommandTalk™	02/05/02	Mulgaonkar, Dodd, Blair, Perna, Hofmann, Martinez
NASA Ames	A. Vera & M Matessa—collaboration research at Ames	02/05/02	Mulgaonkar, Dodd, Blair, Perna, Hofmann, Martinez
Jet Propulsion Lab	HRI, cooperative behavior of robots, smart robot nav, robot software architecture, mod-sim	02/06/02	Mulgaonkar, Dodd, Eicker, Blair, Perna, Hofmann, Martinez, Cheok, Dobbs
Sandia National Labs	UGV programs, physics-based mod-sim, remote manipulation of hazardous objects	02/07/02	Mulgaonkar, Dodd, Eicker, Blair, Perna, Hofmann, Martinez, Cheok, Dobbs
TACOM	Jeff Jaczkowski — Vetronics Overview, Crew Integration & Automation Testbed ATD, Robotic Follower ATD & Vetronics Technology Testbed Demo	3/28/02	Mulgaonkar, Blair, Dobbs, Eicker, Cheok, Mitchell

3 ROBOTICS AND ITS PLACE IN TRANSFORMATION

One might ask, "why is the military interested in unmanned vehicles?" The obvious motivation for this interest is the benefit of using unmanned vehicles to keep soldiers out of harm's way and increase soldiers' effectiveness by providing access to areas that are otherwise inaccessible. A secondary benefit is the reduction in the weight of the unmanned platforms because of the reduced need to protect an occupant (e.g., by armor or environmental controls). Given these general military objectives, unmanned vehicles should have several general capabilities: to

1. Go somewhere
2. Do something
3. Report to someone or something

These capabilities correspond to the basic and enduring requirements that soldiers be able to move, shoot, and communicate.

They also imply that unmanned vehicles include:

1. Locomotion and navigation systems—to get somewhere
2. Mission equipment packages—to do something
3. Communication Links—to report to someone or something.

What is meant by *locomotion and navigation* in this context? Does it mean the ability to negotiate all types of terrain in all types of weather? Does it mean that continuous interaction with a soldier is required for locomotion control and navigation, or does mean that less is required of the soldier?

What does a *mission equipment package* mean in this context? Does it mean that the vehicle carries sensors only, or weapons as well as sensors? How much must the soldier interact with the vehicle to use the mission equipment? Will different operators be needed for the unmanned system and the mission equipment? Do vehicles accept different mission packages, depending on the mission?

What is meant by *communication links* in this context? Do communication links connect the soldier to one vehicle or to multiple vehicles? Do communication links connect multiple vehicles for intervehicle collaboration? What types and amounts of communication flow over the links, and how many interactions take place between soldiers?

Lastly, to what extent should we permit unmanned vehicles do the above things without humans in the loop? What should they do by themselves or in combination with other unmanned vehicles, and what should be the role of soldiers? Answers to these questions will profoundly influence the design of unmanned vehicles as well as the force structures that will operate and maintain them.

To understand why unmanned systems are a critical enabler for the Objective Force[2], it is instructive to examine a few relevant scenarios. In this section, we briefly discuss three aspects of unmanned systems, based on an examination of three sources. The first aspect is the "ensemble"

[2] The Objective Force is the conceptual Army structure of the 2020 era.

concept articulated in many sources but brought to the forefront in the ASB 1999 Summer Study. The second is a blend of the operational concepts under discussion by the current FCS community, including sources such as ARL, the FCS Lead Systems Integrator (LSI), and the U.S. Army Tank-Automotive and Armaments Command (TACOM) Vetronics Technology Integration (VTI) communities. The third is the long-term operational concepts that set the roadmap for the tight integration of robots and soldiers into organic teams that fight together instead of soldiers who use the robots merely as tools with which they fight.

1999 Summer Study Vision

In the 1999 Summer Study, one of the key technology recommendations for producing a lighter fighting vehicle based force with the lethality and survivability of today's heavy ground platforms was the concept of an ensemble of manned and unmanned systems (air and ground). An *ensemble* is a notional way to deconstruct the functions of a heavy platform (lethality, survivability, mobility, etc.) into individual elements that could physically disperse into components of less than 20 tons each. This concept is similar to the way in which a Navy battle group uses specialized components to perform specialized functions (carrier, anti-submarine screen, etc.) Figure 2 is a graphic representation of this concept.

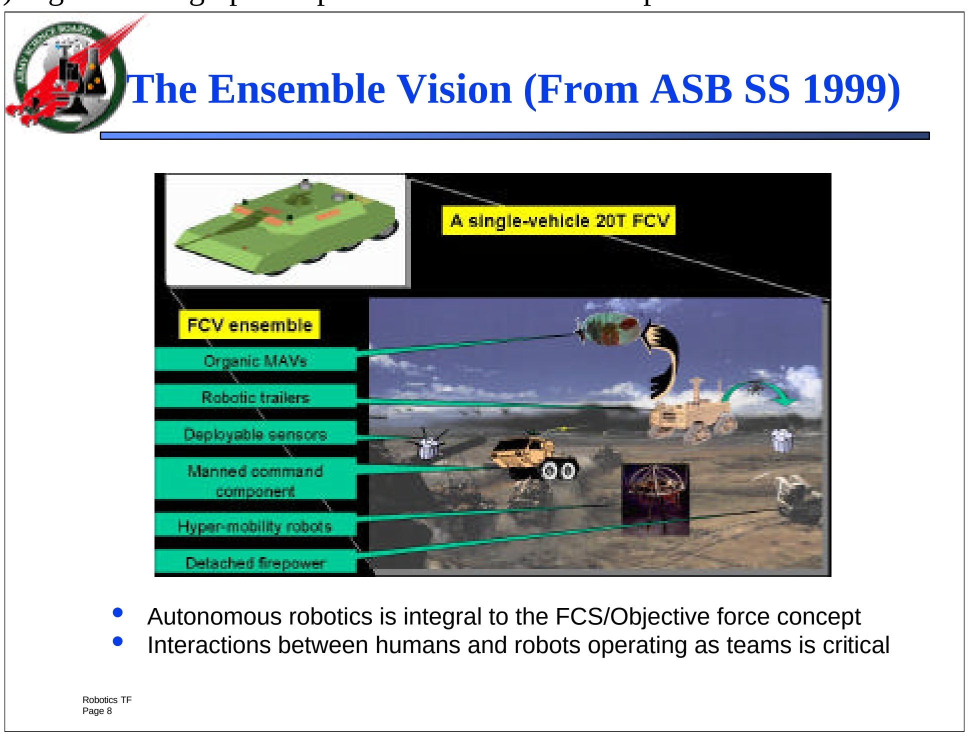

Figure 2. Ensemble Vision

The success of such a scheme requires that unmanned systems constitute the majority of the ensemble components. In addition, the smaller size of the crew controlling an ensemble (compared to the crews that control current platforms) will require ensemble components that are essentially autonomous. Note also that the ensemble consists of autonomous air and ground platforms that operate together in concert with the manned elements of the force. The concept articulated in the summer study was that ensemble components be networked into a common

C4ISR[3] infrastructure, such that they would provide electronic sensor shields around the ensemble. The ensemble elements would have both ground and air mobility and would move and fight as a collective entity to achieve the mission characteristics required by the Force Commander.

The FCS vision

The vision of the unmanned system for the FCS that is the stepping-stone for the Objective Force is still evolving. Different organizations within the Army and its contractor base have developed concepts in which robotic platforms are used with a variety of different capabilities. Figure 3, a graphic from the FCS LSI envisions the use of a number of small (5 T) reconnaissance platforms similar to the ARL Demo III XUV, robotic mules for providing logistical support to dismounted units, and air vehicles of various sizes. While the various scenarios may have different details, they share several common features. They all postulate the use of both ground and air vehicles; they postulate the organic nature of the unmanned entities (i.e., control and ownership at lower echelons, even down to the squad); and they use robots as a screen around the manned entities. Finally, they postulate a lethal capability for the robots (i.e., they do more than reconnaissance, surveillance, and target acquisition [RSTA] missions). On the other hand, they differ in their assumptions about the robustness and availability of robotic capabilities.

[3] C4ISR: Command, control, communications, and computers, intelligence, surveillance, and reconnaissance.

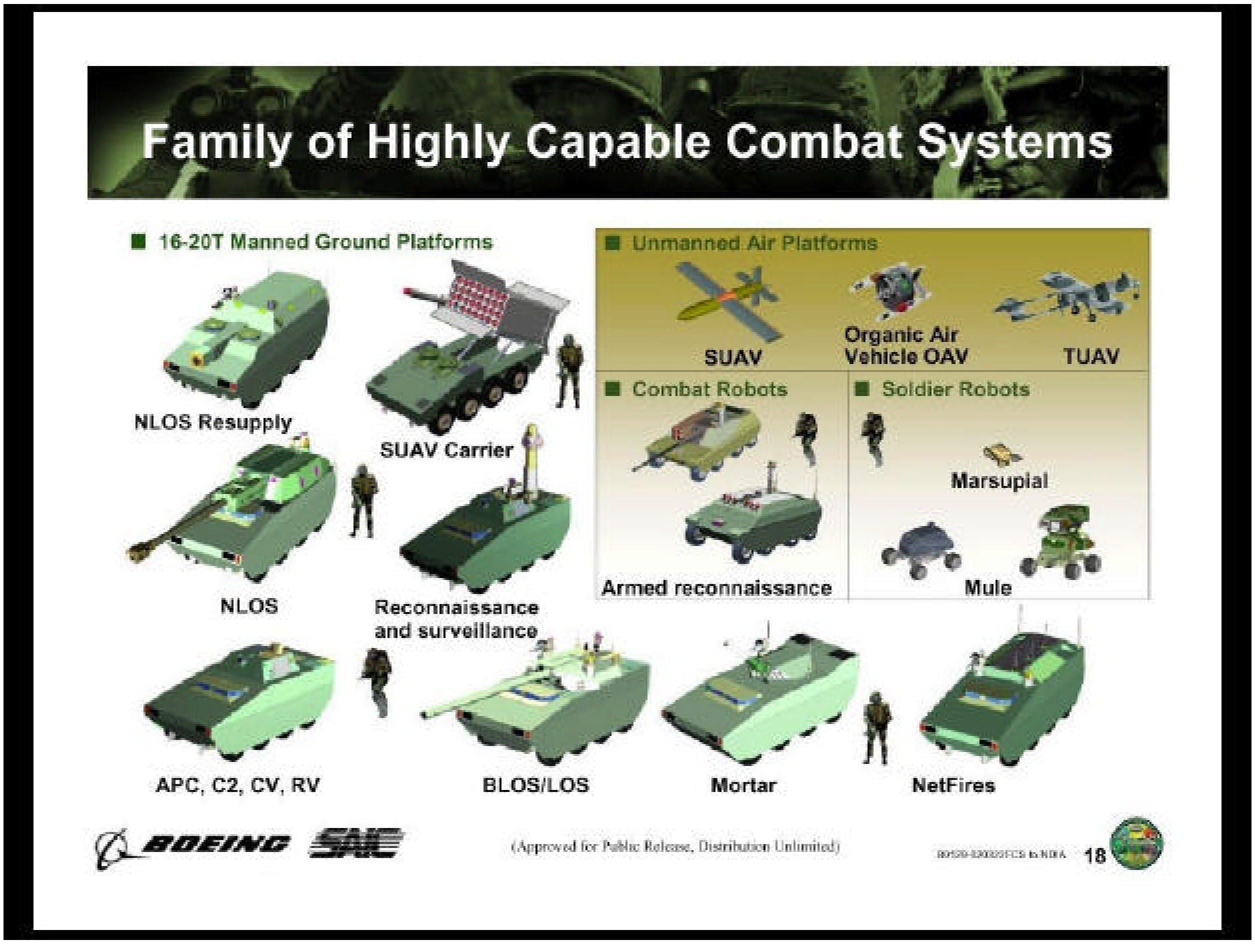

Figure 3. The FCS is envisioned as having several robotic platforms

Given the uncertain availability of autonomy technology, and with a view to accelerate the adoption and use of unmanned systems in the Army, the ASB 2000 Summer Study recommended that the Army focus on semiautonomous robots for logistics. For example, in a convoy operation, humans could compensate for the limitation of today's robots. The TACOM Robotic Follower program that adopted similar goals has developed scenarios where human operators use a combination of inputs to define the path that the robotic vehicles would follow. Figure 4 graphically shows the TACOM vision, and their technical challenges.

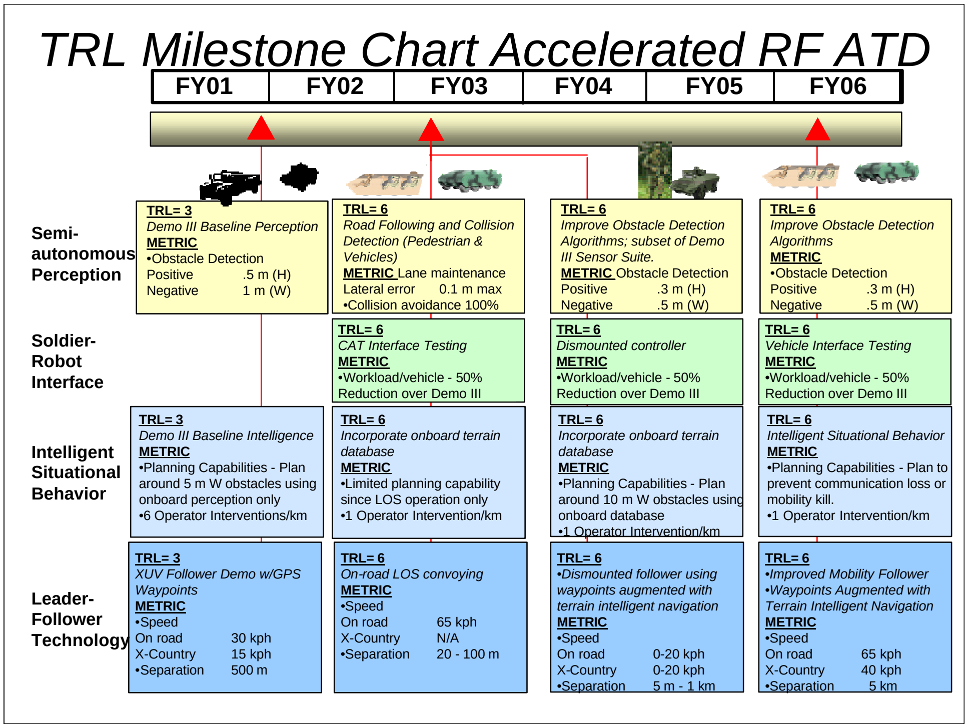

Figure 4. Goals of TACOM Robotic Follower Program

Objective Vision

We believe that a greater integration of humans and robots will characterize the battlefield in the Objective Force era (2020 and beyond). We anticipate that robots will operate in a team, where each team member (whether human or robotic) takes appropriate initiatives as opportunities present themselves. To this end, robots not only must have autonomy and reasoning capabilities about events in the world, but they also must communicate with each other *and* with their human teammates in ways that are natural for humans. No graphic depictions of such scenarios exist outside the realm of science fiction and movies such as the "Star Wars" series. However, these fictional scenarios do indicate that focusing on the natural modes of human-robotic interactions will be a key driver to the development of both autonomy and interfaces.

Interactions vs. Interfaces

The terms of reference for this study use the word "interfaces" to define the subject of the study. The usage rationale for this derives from prior ASB observations that humans will control robots for the foreseeable future. Consequently, interfaces that humans will use to perform these control functions must be developed.

Early in our study, it became clear that the problem we were asked to study was actually broader than interfaces. As the scenarios just indicate, the character of the *interaction* between the manned and unmanned systems changes. In an ensemble interaction, the unmanned components are tasked by the manned components with which they are associated. In the FCS scenarios, soldiers and commanders interact with the unmanned systems by issuing tasks (i.e., RSTA missions) that support the force commander's guidance. In the TACOM Robotic Follower vision, humans interact with unmanned systems by simply performing a component of the task; the unmanned systems then "follow." In a Star Wars scenario, humans and robots interact in a fluid

manner, each observing and responding to the actions, behaviors, and outcomes of prior actions (regardless of whether the actor is human or robotic).

The key insight resulting from the panel's deliberations was that one must first define the interactions, and then build interfaces that (optimally) enable the desired interactions to take place. In fact, one must understand the overlap between the environments in which a robot operates, the robot missions, and the robot's capabilities. It is the interplay between these elements that defines the interactions that must occur between the humans and the robots. The interactions, in turn, drive the interfaces. This interplay is showed schematically in Figure 5. Other fields that successfully demonstrate this interaction definition approach for human-complex automation systems include aircraft flight decks, air traffic control and nuclear power plants. The lessons learned from these environments are critical to the unmanned systems community, but, as our findings show, are not currently understood or applied.

In the balance of this report, we will preferentially use the term *interaction* except in the specific cases where we discuss the particular *interfaces* used to embody an interaction.

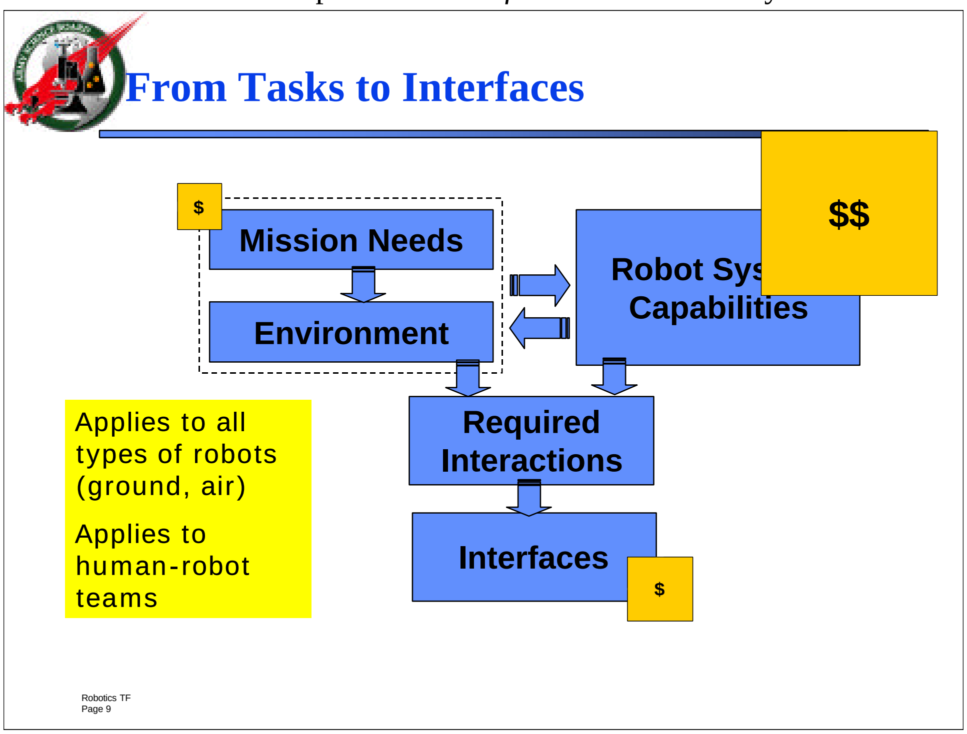

Figure 5. Interactions drive interfaces

<u>Status of Autonomous Systems</u>

From the previous discussion we can see that a critical driver for human-robot interactions is the level of autonomy. Clearly, autonomy will improve over time, but it is useful to evaluate its current status.

Assessing the maturity of autonomy technologies is subjective, especially when applied to ground robots. Further, autonomy in air vehicles is different from autonomy in ground vehicles. One of the key research areas in the field of autonomous unmanned ground systems has been the development of a type of mobility often called *A-B autonomy*.

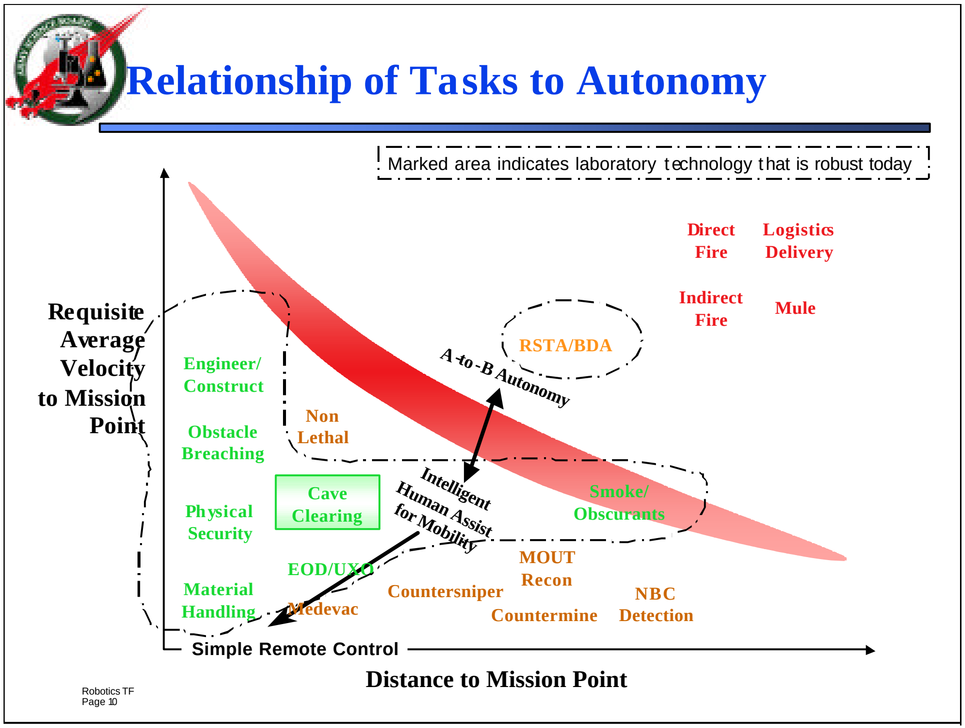

Figure 6. Relationship of Unmanned Ground Vehicle (UGV) Tasks to Autonomy.

Some assert that A-B autonomy for unmanned ground vehicles (UGVs) rests in large measure on mission distance and velocity requirements. From the chart in Figure 3, one can see that many useful functions can be and are being performed by unmanned vehicles without A-B autonomous capability.[4] On the other hand, some missions might well benefit from this capability. It is clear that many of the technologies needed for a full spectrum of unmanned vehicles are in place. None of these technologies are "show stoppers" per se. We believe that there are no programs in place that have a high confidence for developing A-B autonomy. The fundamental thesis underlying the Army's A-B autonomy program, Demo III, is the experimental evidence that shows the inability to teleoperate semiautonomous UGVs cross country at high speeds. There are two key phrases in the latter sentence: *cross country* and *high speed*. If Force Capabilities exist that do not require cross-country or high-speed teleoperation, then the A-B autonomy requirement may not exist. The axes on the chart in Figure 6 are *distance (traveled cross-country*) to mission point and *average velocity*. We made a rough estimate of where each of the Force Capabilities falls on the chart, then coded the Force Capabilities with our estimate of their overall technological readiness. Some comments:

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[4] See the Army UGV roadmap, attached to this document as Appendix C. Section 1.1.4 is particularly relevant to the point made here.

- Many capabilities exist. We estimate that all the needed component technologies are at a sufficient level of technical readiness that only the will remains to develop and deploy such capabilities
- A number of Force Capabilities do not require A-B autonomy.
- We estimate that the capabilities on the top right of the chart do require A-B autonomy. The Army Science and Technology (S&T) community must decide whether these capabilities are critical to the success of FCS
- The shaded region in the middle is a zone on one side of which A-B- autonomy is clearly required, and on the other side of which teleoperation of some sort is acceptable.[5]

Technology Maturity

Attributes	Objectives					
	FCS Best Estimated Need	Current	April 2003 Status	April 2003 Risk	April 2004 Status	April 2004 Risk
Performance						
Cross-country mobility (day)	40 MPH	10 MPH	30 MPH	M*	40 MPH*	M
Cross-country mobility (night)	25 MPH	5 MPH	20 MPH	M*	25 MPH*	M
Physical						
Mobility module size	10 ft^3	14 ft^3	10 ft^3	L	10 ft^3	L
Mobility module weight	180 lbs	180 lbs	180 lbs	L	180 lbs	L
Environmental						
Temperature Max/Min.	-50°,+125°F	+40°,+105°F	+40°,+105°F	L	+40°,+105°F	L
Programmatic						
Test Environment	Field Test	Limited Field	Field		Field	
Unit Cost (By calculation)		$370K/unit	$370K/unit		$370K/unit	
*Demonstrated/Evaluated on larger platform, e.g., NAC 8X8 Hybrid Electric or new DARPA UGV.						
Overall TRL Level	NA	3-4	5		6	

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Figure 7. Estimated Maturity of Autonomous Land Navigation

Figure 7 shows our estimate of the maturity of the autonomous land navigation capability demonstrated by and extrapolated from the ARL Demo III program. It shows that under certain bounded conditions, autonomous operations are feasible. For example, we believe that autonomous cross country surveillance could be carried out by XUV type robots over rolling terrain, using the technology available today. Similarly, robotic followers could be built in a robust fashion today.

While additional research in robotic autonomy is clearly required, we believe that an appropriate focus and investment in maturing the available technology is not only justified but critical to the success of transformation efforts.

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[5] We recognized the need for a similar matrix that addresses air vehicles, but time constraints for the study prevented its development.

It is important to ask whether any of the functions shown in Figure 7 would be better performed by aerial vehicles instead of ground vehicles. Table 2 shows the potential distribution of functions between UAVs and UGVs. For example, engineering and construction must be performed on the ground. On the other hand, indirect fire can be provided by air vehicles, as has already been demonstrated in Afghanistan by Predator UAVs carrying Hellfire missiles.

Table 2. UAV and UGV Functionality.
Shaded areas represent tasks that could be performed by respective vehicles.

Tasks (from Figure 6)	UGV	Low-Flying UAV	High-Flying UAV
Logistics Delivery			
Mule			
Engineering/Construction			
Obstacle Breaching			
Physical Security			
Material Handling			
Nonlethal			
Cave Clearing			
EOD/UXO*		(Detection only)	
Medevac			
Countersniping			
Countermining		(Detection only)	
MOUT[+]Reconnaissance			
NBC[‡] Detection			
RSTA/BDA			
Direct Fire			
Indirect Fire			

*EOD: Explosive ordnance disposal; UXO: unexploded ordnance.
[+] MOUT: military operations in urban terrain
[‡] NBC: nuclear, biological, and chemical

The robotics community clearly recognizes that the challenges to autonomy for UAVs are different (and some would argue, simpler) from those for UGVs. What is not widely recognized in the community, is that even when certain functions could be assigned to UAVs, high-flying UAVs differ from those that operate close to the ground. Low-flying UAVs must contend with challenges such as trees, air currents, buildings, dirt and flying debris, which might make autonomous versions as difficult to build as autonomous UGVs. In addition, UAVs expend significant energy to lift their own weight and that of their payloads, so they are inefficient in applications that require long periods of stationary operations and those that require them to move significant weight.

We believe that the FCS LSI should focus effort on understanding this trade space and create a roadmap for the optimal distribution of functionality among various classes of autonomous and semiautonomous platforms.

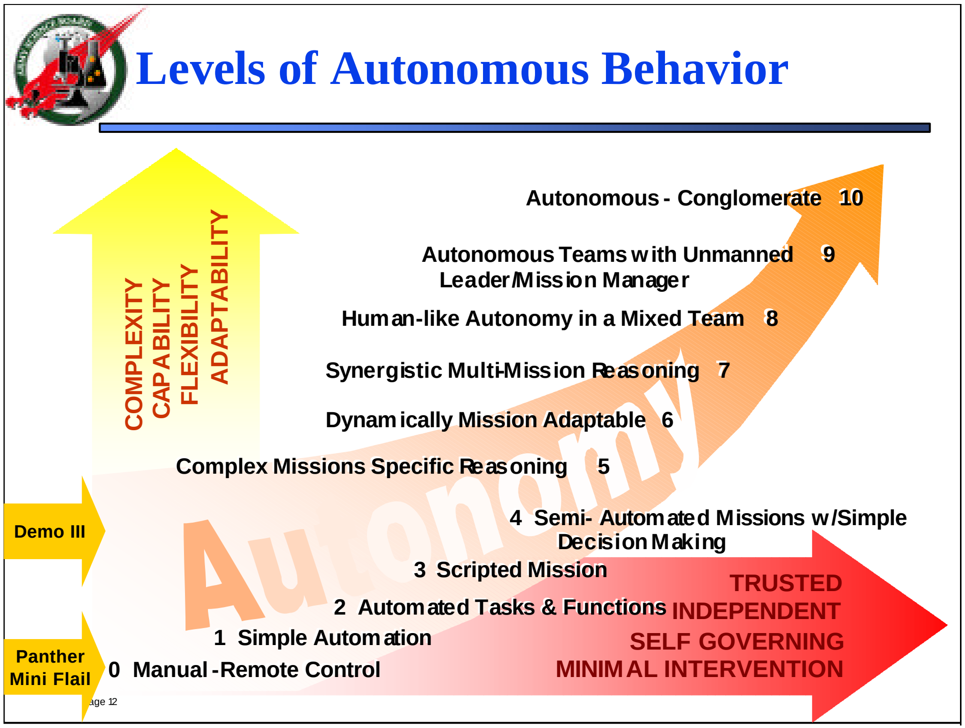

Figure 8. Levels of Autonomous Behavior

As noted above, we must understand what a robot can do if we are to define human interactions that are required. In order to add some rigor to the discussions, we defined levels of autonomy in order to parameterize robot capability. These levels are shown in Figure 8 and listed below.

0. Manual Remote Control, like a remote controlled toy
1. Simple Automation
2. Automated Tasks and Functions, like a Hunter
3. Scripted Mission, like an Shadow or Predator UAV
4. Semiautomated Missions with Simple Decision Making, like an Cruise Missile
5. Complex Missions-Specific Reasoning
6. Dynamically Mission Adaptable
7. Synergistic Multimission Reasoning
8. Human-like Autonomy in a Mixed Team
9. Autonomous Teams with Unmanned Leader or Mission Manager
10. Autonomous Conglomerate.

In the UGV world, fielded systems such as the Panther and the Mini-Flail are at Level 0. They are simple remote-controlled devices in which the operator visualizes the actions of the robot through direct observation, and controls the robot through low-level commands. Demo III's XUV is at Level 3 or 4, where the robot performs a significant amount of sensor-based, self-directed operation. There are no extant systems at Levels 9 and 10, which represent only vague concepts more akin to the "droids" of science fiction than any real system under development today.

4 SOLDIER INTERACTIONS AND INTERFACES WITH UNMANNED SYSTEMS

Once we accept the notion that interaction precedes interfaces, it is useful to step back from the technology and look at how humans interact with (or use) "things"—tools, weapons, other people in general.

Considered from that viewpoint, robots are simply a class of things with potential capabilities ranging from those of ordinary power tools to those of humans and possibly beyond. This spectrum of potentials confuses the discussion. A robot is not a clearly defined thing like a rifle or an entrenching tool. A robot's use depends upon its intended function and capabilities.

In the near- and mid-term, humans will closely control most military robots (ASB Summer Study 2001). The robot's ability to perform autonomously in the unstructured military environment will still be limited. Systems like the teleoperated *Panther* minefield proofing unit used in Bosnia will be relatively common. However, the ARL Demo III RSTA robot already has demonstrated significant ability to go where it is told in the field, gather information, and find its way home without further human control. Using a robot like the *Panther* differs only marginally from driving a vehicle. Using the Demo III robot would leave a soldier free to do other tasks while the robot carried out its own mission.

The performance of the Demo III robot is quite amazing to those of us who have watched the program progress over the past 20 years. The next 20 years predictably will show far greater success. The concept of a robotic mule (RoboMule) for the Objective Force soldier was clearly supported by the ASB 2001 Summer Study. In the far term, after 2010, such RoboMules will have far more capability than the Army leadership now believes possible.

RoboMules will not require self-awareness but will require enough intelligence to know the soldiers to whom they are assigned and be able to communicate verbally with them. They also will need to communicate electronically with other machines and with soldiers. They will need to find their way to where they are told to go and to take care of their own refueling. They must know enough to ask permission before leaving their assigned soldiers to get fuel or pick up routine supplies from some other area. They should have more capable sensors than a human and the ability to travel at least 50 mph on improved roads. Off-road capabilities should include a travel speed of 20 mph, 60% forward and side slope negotiation, and the ability to cross a ditch 4 feet wide. In addition, they should have the intelligence necessary to recognize impassable terrain at a level at least similar to human ability.

A RoboMule will require arms—two or more—for loading and unloading itself or other vehicles (and possibly other tasks). It will require all-around awareness, despite the visual obstruction of its cargo area; naturally, it will not be limited to one pair of eyes like a human. It will need the ability to open and close the top of its cargo area for loading and unloading as well

as to help with the wounded, and safely load and unload litters.

The RoboMule is on the other end of the robot spectrum from the “dumb” Panther. The basic point here is that soldiers will interact with the semi-intelligent RoboMule much as they do with other soldiers. One of the more challenging tasks that a human performs when interacting with robots is that of analyzing and reacting to information. The Rotocraft Pilot’s Associate (RPA) demonstrates how to automate such tasks successfully. In the RPA program, automated decision tools *coupled with mission execution and planning modules* reduce the cognitive workload for humans. The RPA system has allowed AH-64D Apache helicopter pilots to control another UAV (Hunter) in addition to their own helicopters in real time and in a real operating environment (Fort Polk JCF-AWE, and at the NTC with the 101st Air Assault Division).

In sum, soldiers will use robots in many different ways, just as they use the tools, weapons, and fellow soldiers with whom they work today. The task and the tools at hand, whether robots or ratchet wrenches, will determine how the soldier uses them. Unless robots can perform tasks better than humans, and the resulting human-robotic combination produces a more capable fighting force, there is no value in fielding them. Initially, the human-robotic interface will likely involve simple jobs not significantly different from those accomplished with current military vehicles. As robotic capabilities increase, soldiers will in general give robots direction rather than control them directly. Ultimately, soldiers will work with robots in the same way as they do with other soldiers.

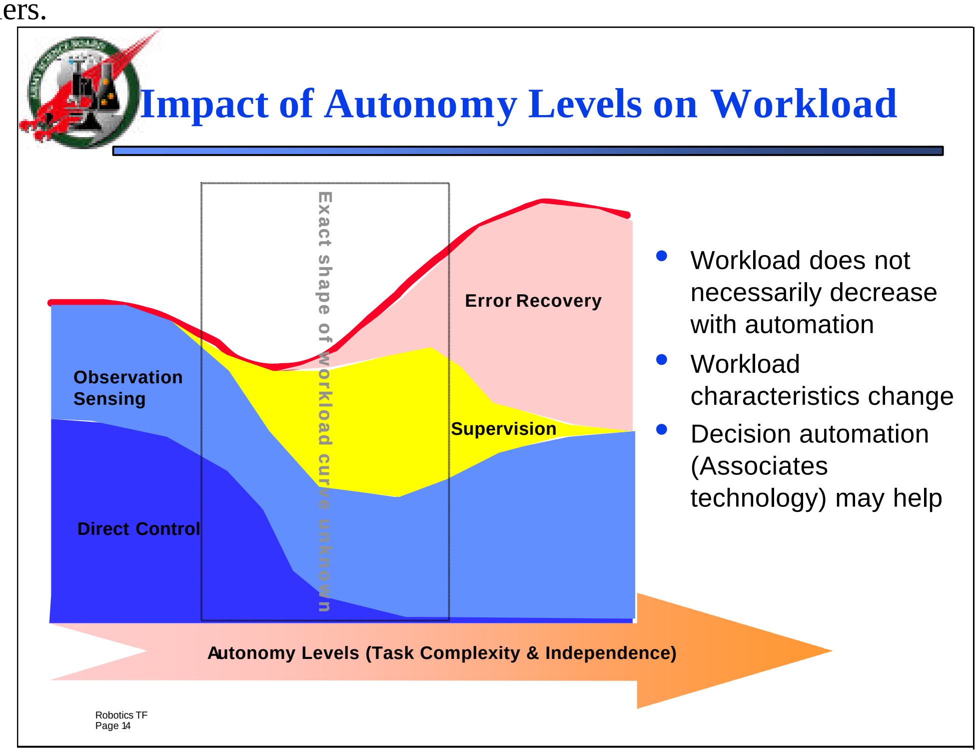

Figure 9. Impact of Autonomy Levels on Workload

It is important to understand the way in which assumptions about autonomy and robot system capability factor into the design of human robot interfaces.

As Figure 9 shows, the requirement for robots to execute certain functions autonomously varies. Even when autonomy may be required, the environment may be complex enough that full autonomy is not achievable. Further, in complex environments with semiautonomous robots, the

level of supervision that is required may actually put a heavier cognitive load on the human than simpler environments or simpler robots.

In a systems-engineering approach to designing complex systems, we would have to start by understanding the tasks that they have to perform, the capabilities of the autonomous systems, and the failure modes. This analysis then defines the interactions required between the humans and the robots either to control a system's capabilities or to react to its deficiencies. The required interactions are then mapped to the interfaces that allow the humans to perform the proper interactions.

In this context, there are three general forms of interaction modes, which parallel autonomy levels: remote control, teleoperation, and telerobotics of the soldier/robot interface.

Remote control interactions are usually accomplished with simple operator interface designs. Operators have line of sight to the unmanned vehicle, so their eyes provide the sensory feedback needed for vehicle navigation and locomotion control. Feedback to control specific on-board payloads also comes from direct sensory feedback or through simple displays. Control interfaces for these vehicles usually are simple in design, given the constrained nature of the interaction. Examples of such vehicles are remote-controlled model airplanes and cars. Military ground examples are the Mini-Flail and Panther. These types of systems usually require one operator per vehicle. The components of these systems are much the same as those found in any vehicle-based system. What is unique to the world of unmanned vehicles is the dominance of electronic information flow between the soldier and the unmanned vehicle. There is the vehicle that, depending upon the mission, is more or less "smart." There is the soldier-vehicle interface consisting of display and controls. Finally, the soldier will oversee or direct the system to accomplish the mission or task to the maximum of its capability.

We cannot overemphasize the importance of the soldier getting required information in a timely manner and in a useful form. On some missions, as unmanned vehicles become even more capable, soldiers will command several robots and robots will communicate among themselves to solve problems. These factors require the development of interfaces that assure timely information flow at various levels of employment where changes occur rapidly.

Teleoperation interactions require more sophisticated display and control interfaces because navigation, locomotion control, task execution, and vehicle status monitoring are not performed by line of sight. Therefore, soldier interface displays must be capable of providing appropriate and timely information feedback that is formatted in ways that allow operators to successfully control unmanned vehicles and their mission equipment packages. Controller interface designs must permit operators to send commands to the vehicle, based on display information feedback, that are timely, appropriate, and accurate enough to accomplish the mission successfully. Some believe that unmanned vehicles of this type evolved from manned vehicles. More specifically, these include manned vehicles designed to achieve near daytime operational capability 24 hours a day in nearly all weather conditions, and those designed to operate in a "closed hatch" mode during NBC operations. To achieve the above goals, many of these manned vehicles employ advanced sensors that provide visual and auditory feedback about the environment. These sensors often operate in ranges of the electromagnetic spectrum (I2, IR, RF, MMWR, and LADAR[6]) that

[6] I2: image intensification; IR: infrared; RF: radio frequencies; MMWR: millimeter-wave radar; LADAR: laser radar.

exceed the direct sensing capability of the vehicle operator's eyes and ears. Therefore, operational capability additional to that of the unaided human sensory system can be achieved. The visual displays used in conjunction with these sensors include helmet-or panel-mounted displays. Operator control interfaces to slew sensors help to overcome sensor field-of-view limitations. Helmet-mounted displays, the sensors are often slaved to the movement of the helmet to provide slewing control. Vehicles having the above sensor capabilities often integrate locomotion, navigation, target acquisition, fire control and vehicle status feedback information into a limited number of operator interface displays. In many cases, soldier interfaces designed to control these vehicles and perform mission tasks are also integrated into a common module. Many of the control system outputs are electrical or electro-optical signals that go to power-assisted actuators. Therefore, a transition from a manned to unmanned vehicle fundamentally involves providing links for sending signals from sensors on board the vehicle to soldier display interfaces in remote operator stations. Links also must be provided to send signals generated by the operator control interface back to vehicle actuators, thus enabling soldiers to control the vehicle while they remain out of harm's way. It is no surprise that remote-control stations often look like in-vehicle control stations. The assumption is that whether a soldier is in the vehicle or remote to the vehicle, the display/control interfaces and layout should be similar. Military ground examples of this would include the Man-Portable Remote System (MPRS).

The teleoperation interaction approach usually requires one operator per system. Operator data requirements for effective control and display usually demand large bandwidth for transmission. Additionally, locomotion and navigation control of these systems, especially ground systems, is difficult because of sensor and/or display limitations and lack of operator motion cues.

The bulk of the current requirements for unmanned ground systems in the Army are in applications of remote-controlled or teleoperated systems. The Joint Program Office (JPO) at Huntsville is focused on satisfying these requirements.

Telemanagement (aka telerobotics) interaction approaches require a teleoperation capability, but provide more capability for autonomous action. The goal is to provide as much as possible of the autonomous capability at the vehicle level in order to reduce the data transmission requirements between vehicles and remote display and control interface sites. Reducing transmission requirements to reduce bandwidth requirements is critical. In this design approach, adding more autonomy or off-loading actions reduces operator workload and provides increased performance over teleoperation. It can also enable the operator to operate more than one vehicle, i.e., one on many (force multipliers). When these systems become smart enough, operators will assume higher-level roles and interact only on functions and tasks that a priori are determined to require soldier input. Examples might include planning a mission that would entail defining its destination, identifying targets to kill, and intervening when emergencies occur. For operational effectiveness, however, highly autonomous robots may require operator control and display interfaces more complex than those required by teleoperation. This statement is based on the assumption that successful intervention in emergency situations may require telepresence or perceptual immersion. In addition, the assurance of timely and appropriate inputs may require sophisticated decision-aiding displays and their associated software. A current ground vehicle with a rudimentary version of what we call telemanagement properties is the ARL XUV vehicle that uses the Real-Time Control System (RCS) architecture. RCS is one of the most promising architectures for providing "smart" vehicle control systems. (James Albus and Alexander Meystel

described RCS in *Engineering of Mind, [2001])*. This hierarchical planning and control architecture is compelling from a number of perspectives. For example, it is *isomorphic* with general stereotypes regarding intelligent behavior generation, management and organization. These features have significant implications for soldier-machine interface design. The RCS version currently employed in the XUV vehicle is capable of navigation and locomotion control. This capability is advanced enough that it elicits *anthropomorphic* comments from soldiers. Example statements include “Watch, he (referring to the vehicle) is going to make a turn,” or “He is trying to make up his mind.” The development and fielding of “smart” and “smarter” unmanned vehicles becomes more feasible each year as the weight, power, cost, and size of computing power, displays, and sensors decreases.

Figure 9 shows that as the level of autonomy for any task increases, the nature of the interaction between the human and the unmanned system changes. The human goes from being a detailed task-level controller, requiring full-time interaction, to more of a supervisory role; a role that is more instructional, more involved with what to do than with how to do it. Feedback comes more by notification and query than by continuous monitoring, unless there is an emergency or highly complex or risky task.

It is interesting to correlate the information in Figure 9 with that in Figure 7. In Figure 9, the area between the teleoperation functions and the autonomous functions is a critical region—one where some autonomy is possible but is not robust enough for full-time reliance. Humans must take control and teleoperate the robots whenever things do not go according to expectations. The interactions that enable the humans to understand the context of the failure and the potential remedies are significant challenges. Very little work has been done on computational representations of such spatio-temporal context and on the mixed-initiative nature of the interactions.

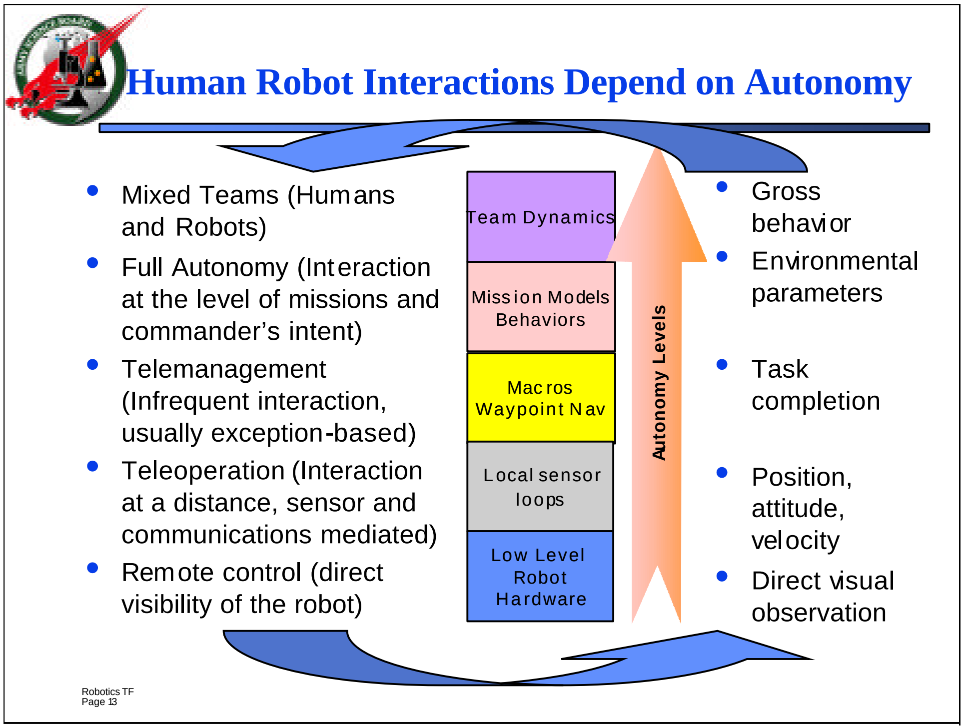

Figure 10. Interactions and Autonomy.

For force multiplication, it is desirable that individual humans control multiple robots. Today, Predators require a crew of 24 humans to manage all aspects of a mission. In future, the hope is that with appropriate autonomy and interaction modalities a single soldier would control multiple, perhaps four, robots. If this is achievable, the value to the Army should be significant.

The question "how many robots can one person control" is often asked, but is extremely challenging to answer. The answer depends upon all of the factors we have discussed in the previous sections: the level of autonomy assumed, the level of intelligence in the robot (ability to deal with unexpected situations), the complexity of the environment, and the criticality of the task. At the lowest level of autonomy (remote control), the connection between a controller and a robot is only 1:1. As autonomy increases, a soldier might be able to task a robot to initiate a mission and then devote attention to other robots, returning periodically to check up on the progress of individual robot mission. In an environment where everything works as planned, there is no theoretical limit to the number of robots a soldier could control. Air traffic controllers in the U. S. airspace routinely manage the positions and movement of dozens of aircraft (primarily through effectively structuring what is otherwise an unstructured environment). However, in environments that one cannot structure and where things do go wrong, the commander or operator has to keep a mental map of what is happening—which limits the span of control. For example, in a standard military environment, the commander's span of control is usually 3 to 5 subordinates. If we assume the existence of robots with the *same level of capability as humans*, the span of control is unlikely to be much greater than that. This span of control is similar to what one finds in typical civilian organizations.

In the future, humans will have to work with multiple robots and the robots will have to work with each other. Therefore, some argue that the design of the human control and display

interface with "really smart" unmanned machines should eventually duplicate the same modalities as human-human interactions, on the assumption that one simply tells the machine what to do and when to do it. The machine then figures out how to comply and verbally reports back when it completes the assigned task or mission. It also provides interim progress reports if they are desired. Only if an autonomous unmanned vehicle(s) encounters a situation beyond its capacity will it ask for external human or machine assistance. This capability to interact and dialog in a human-like modality is particularly important when multiple soldiers and robots work together in integrated teams. Each needs to understand intuitively what all of the others are doing.

4.1 HUMAN-ROBOT INTERFACES AND TODAY'S ROBOTIC SYSTEMS

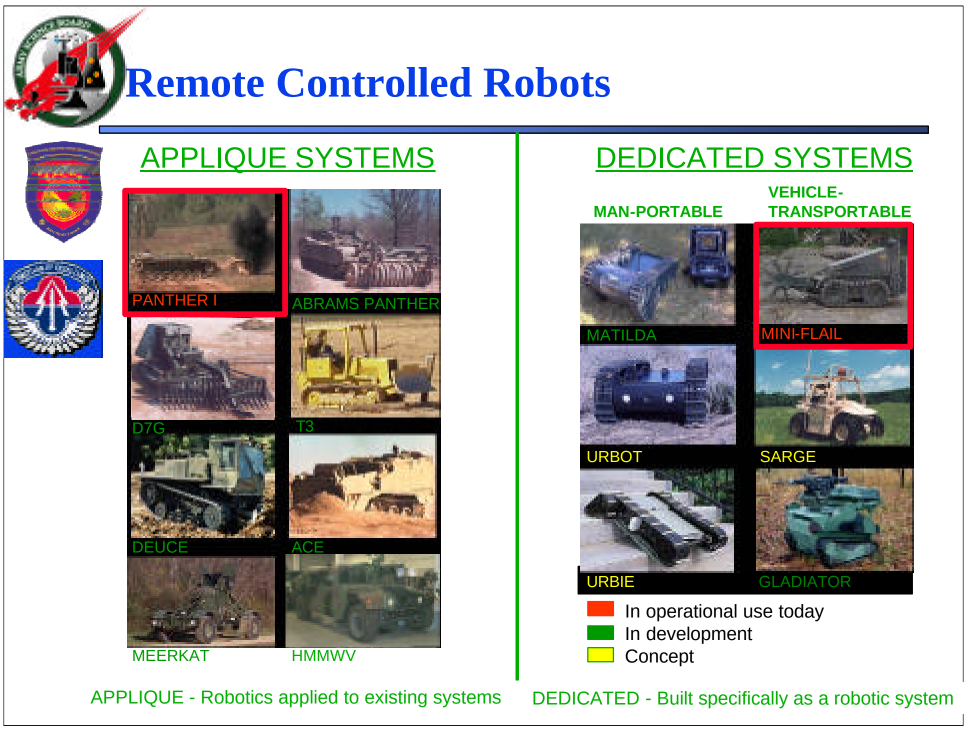

Figure 11. Remote-Controlled Robots

Figure 11 graphically shows the remote-controlled ground robots being developed by the Army. Of these, only the Panther and the Mini-Flail are operational today.

HRI for Remote Controlled Robots

Rugged, robust devices
Key issues are engineering

Human-Machine Interface (HMI)		
Baseline / Block I (FUE 07)	**Upgrade / Block II (FUE 14)**	**Upgrade / Block III (FUE 17)**
	OCU displays positions of MBU, OCU, friendly and enemy elements in UTM	
Modular payloads mountable & dismountable in 10 minutes	Modular payloads mountable & dismountable in 5 minutes	
OCU not visually detectable by unaided eye at night beyond 20 meters*	OCU not visually detectable by unaided eye at night beyond 15 meters*	OCU not visually detectable by unaided eye at night beyond 10 meters*
Capable of operation while wearing cold weather gloves		Capable of operation while wearing mittens
video recording capability at UCU		
OCU weight 20 lbs. including batteries	15 lbs. including batteries	10 lbs. including batteries
earpiece to hear MBU sounds		
OCU power without battery change - 2 hours	OCU power without battery change - 4 hours	OCU power without battery change - 8 hours
	OCU display digital map	display standard military symbols and overlays

Courtesy AMRDEC

Robotics TF
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Figure 12. Interfaces for Remote-Controlled Robots

Figure 12 indicates the fairly simple level of the interfaces required to operate such remote controlled robots. The key challenges in such displays are engineering in nature: building the displays cost effectively and making them rugged and survivable.

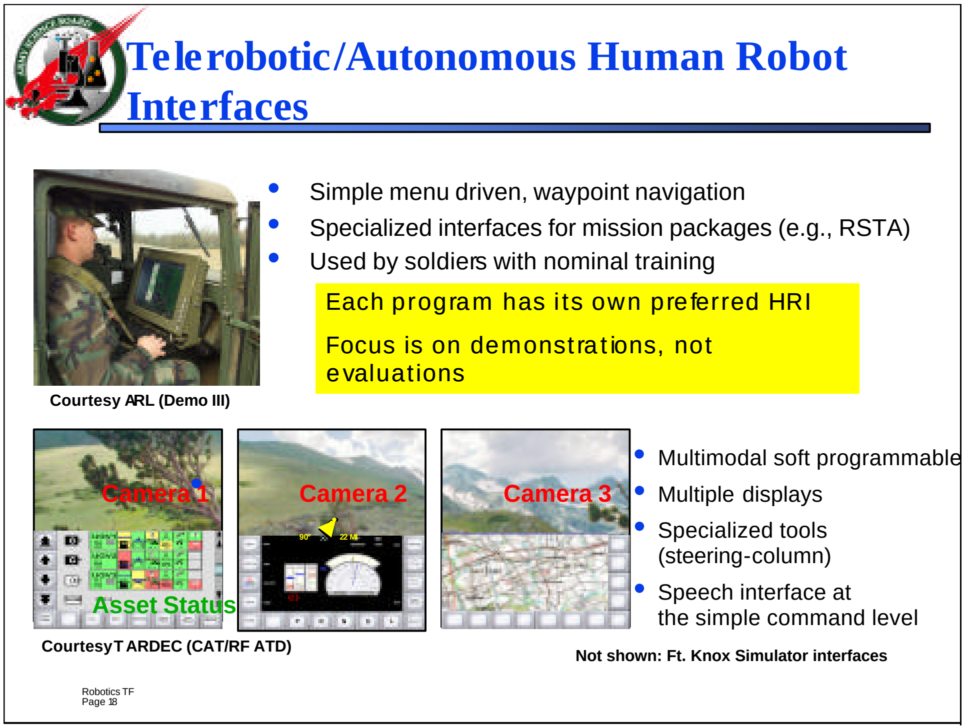

Figure 13. Human-Robot Interfaces for Intelligent Semiautonomous Robots

Figure 13 shows the interfaces that have been developed on Army programs dealing with intelligent semiautonomous robots. The photograph on the top left shows the Demo III flat-panel display in use. Demo III robots are tasked by using a point-and-click interface to provide the robots with waypoints, destinations, and simple constraints (such as "hug the tree-line").

The three screen captures in the bottom half of the figure show the visualization interface under development for the Crew Automation Testbed (CAT) ATD program. This interface will be used to task the Robotic Follower (RF). The interface consists of three panels with a full suite of software reprogrammable buttons, as well as a hardware "steering-wheel" interface with hardware buttons and controls.

Not shown in the figure is the robotic interface under development at Fort Knox for use with the robotic simulators in the Battle Lab.

The panel observed that even though there was overlap between the work of contractors on the Demo III and the CAT/RF programs, the user interfaces were different. There had been no experimentation on Demo III to identify the effectiveness of the interface, and therefore, no lessons learned that could be transferred to the CAT/RF program. Further, the Demo III interface seemed to be primarily a mechanism to task the robot and to allow the demonstration of the autonomous capability of the XUV vehicle. Similarly, the CAT interface was an exercise in building a highly reprogrammable, flexible crew workstation, rather than a robot controller per se.

A key panel finding was that the stovepiped nature of development within the S&T community and the lack of user pull, allowed the various communities to focus only on their own narrow technical goals. Even the demonstrations that each community was planning were uncoordinated and not focused on a common user-defined problem (i.e., FCS Block I scenarios).

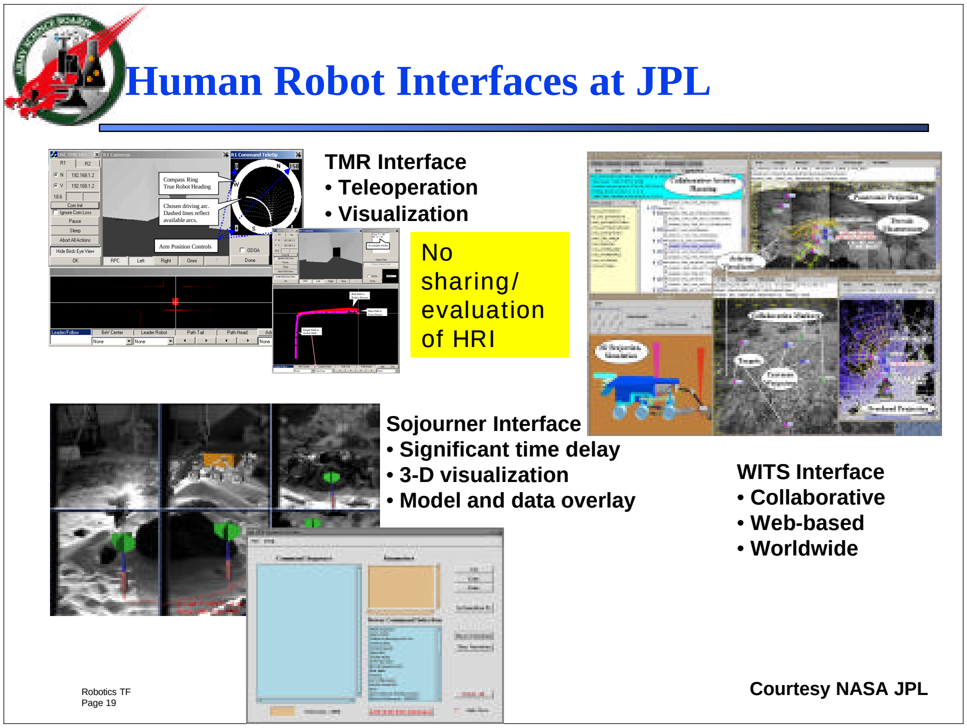

Figure 14. Human-Robot Interfaces Developed at JPL

This problem is illustrated in Figure 14 by three human-robot interfaces developed at the NASA Jet Propulsion Laboratory (JPL). The interface on the top left was developed by JPL researchers for the DARPA Tactical Mobile Robots (TMR) program. The interface on the bottom left is the tool used to control Sojourner, the first Mars rover. The figure on the top right shows the interface for the Wide Area Telerobotics System (WITS) that will be used to control the next-generation Mars rover in a worldwide Web-enabled distributed manner.

Again, no metrics were used to evaluate the efficacy of each of the interfaces. It appeared that each development team had its own human-robot interface subteam that "invented" its own interface tool from scratch. Without appropriate metrics, no mechanism can evaluate aspects of the interface that operate well, or aspects that need to be further developed.

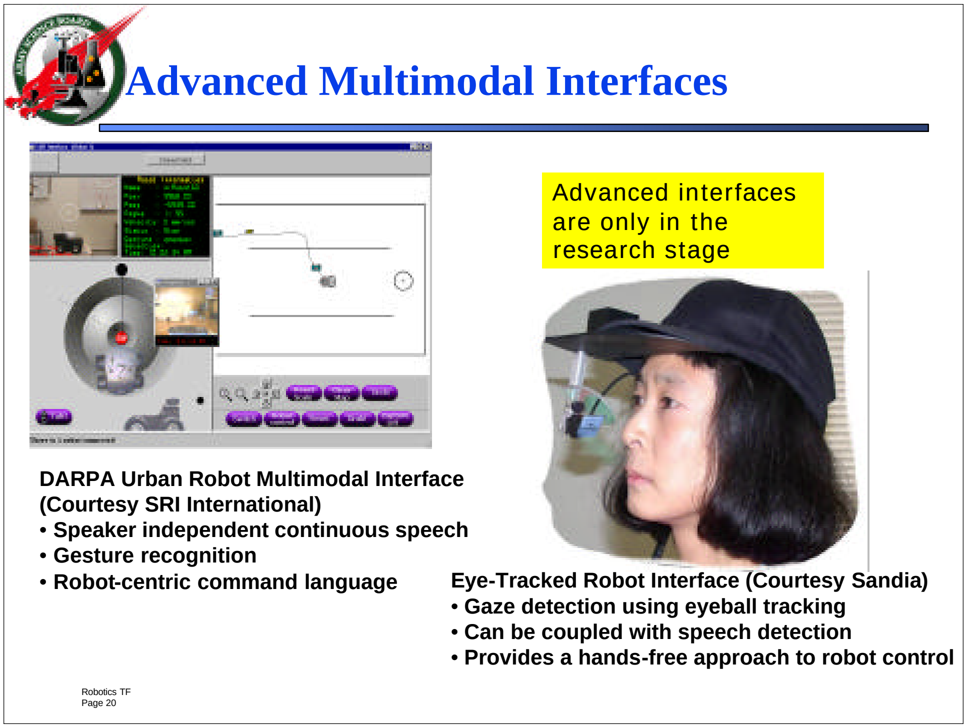

Figure 15. Advanced Multimodal Interfaces

Figure 15 shows two research interfaces more sophisticated than simple mouse-windows mechanisms. The left-hand figure shows a multimodal interface developed by researchers at SRI International on a recent DARPA program. The interface uses speech, gestures, and contextual references to objects in a scene (as seen by the on-board robot camera) to command the robots. The figure on the right shows an eye-tracker developed at Sandia National Laboratories that allows the wearer to refer to robot commands by simply glancing at appropriate commands projected into a heads-up display.

Since neither of these programs is tied to any real application, it is impossible to ascertain whether such interaction modalities are useful, or even necessary. While they represent significant advances in terms of human-robot “dialog,” value can only be determined within the context of real applications. For example, will ambient noise affect speech recognition adversely? What will be the results of the interaction if commands have to be constantly repeated? Such questions can be answered only if the community develops a core set of metrics and performs a series of experiments in realistic environments.

What is common to all these examples is that they focus on interfaces, not interactions; they lack a systematic evaluation of the relationships between missions, robot capabilities and interactions; they have no metrics for the evaluation of performance; and they constitute technology demonstrations, not solutions.

For example, the Demo III vehicle “resorts to full teleoperation” if it cannot reason about the path on its own in three attempts. So, while there are interaction modes in the interface to provide the robot with waypoints and goals, there is no effective teleoperation mode. Users have to resort to remote control, direct observation of the robot from a chase vehicle, to perform the error recovery tasks.

The research community has recognized this problem. A recent joint DARPA/National Science Foundation (NSF) workshop on human-robot interactions concluded that multidisciplinary research was needed in the area. They recognized, as we did, that suitable metrics, and focused experimentation in defined environments were critical to the success of the field. For further information on the conclusions of the workshop, please refer to: http://www.aic.nrl.navy.mil/hri/nsfdarpa/

4.2 INTERACTIONS IN OTHER COMPLEX SYSTEMS

Systematic experimental work should be conducted to identify what Army functions and tasks can benefit most from the use of unmanned vehicles; determine which class of interaction should be used for the identified tasks and functions; and specify the design of the soldier control and display for the selected classes and functions/tasks. This effort should embrace the full repertoire of developmental tools including analytical efforts, simulation, field experiments, and prototype development. The failure to perform systematic experimental work to gain effective design guidance for interfacing humans with advanced semi-autonomous systems will lead to undesirable outcomes. Researchers in a number of fields learned this lesson the hard way. For example, commercial airlines have achieved enhanced system performance by using advanced flight management systems that are electronically or electro-optically linked to actuators that control aerodynamic surfaces and engine performance. Such systems make an airplane "smarter," in that they enable the airplane to perform many tasks that previously required the full time attention of the crew. The introduction of these technologies, when correctly designed and interfaced with the crew, has not only led to safer, more efficient flight, also has done so at a reduced cost. On the other hand, when the crew interface is incorrectly designed catastrophic outcomes can occur. For example, a "smart" airplane may take some "not so smart" actions under certain conditions that are unknown by the crew. When the crew finally becomes aware of the problem, appropriate corrective actions may be too late. In some cases, crew interfaces are designed so as to induce input instruction errors. In the worst case, these errors lead to catastrophic results and in the best cases; they result in losses of time and fuel. The medical equipment field has also experienced its share of catastrophic results due to inadequate control and display interface design. For example, during cancer therapy, remotely controlled "smart" machines administered radiation overdoses to patients because of faulty human control and interface design. Some of these overdoses killed patients. Three Mile Island, and many other complex human-machine environments have resulted in adverse consequences. The message is clear: attention must be paid to the human control/display interfaces and the underlying architectures of complex smart systems if humans are to successfully interact with them and they are to achieve their design objectives.

During this study we tried to determine two things: first, whether the Army has work in progress to identify the tasks and functions that would benefit most from the application of manned vehicles; and second, whether work to develop effective soldier interfaces with unmanned vehicles was also in progress. Emerging results seem to indicate that for the most part this was *not the case*. Inarguably, much good work is in progress in a number of places. Unfortunately, we found very little quantifiable data from systematic efforts to identify the tasks and functions that could most benefit from the use of unmanned vehicles with various capabilities. Similarly, we found very little data to support the design of soldier interfaces with unmanned vehicles designed to execute military tasks. To some extent, these findings are understandable, given the maturity of

some levels of unmanned-vehicle-enabling technologies. However, history shows that success depends on the early introduction of the ultimate operator and maintainer (the human) into the design loop. Designs that do not heed human control interface issues produce results that can have catastrophic consequences or at the very least will degrade system performance.

We surveyed a number of automation-related research efforts concerned with crew-station design in the aviation field. The record shows that making the appropriate task assignments between the pilot and the machine as well as correctly designing the pilot-computer interface are essential to efficient operations. We posit that the same is true of the soldier–robot system interface.

The factors that drive unmanned system interactions are

- The mission/operational environment and overall task complexity
- The desired ratio of soldiers to unmanned systems
- Line-of-sight vs. non-line-of-sight operation
- Communication bandwidth availability
- Technology availability and cost
- Force/team OPTEMPO and degree of operation risk or threat.

These factors drive systems design and dictate the level of soldier-system interaction as well as the technology design tradeoffs that in turn determine interface requirements. The interface, regardless of the technology and degree of automation, must provide a soldier with the information that he or she needs, when they need it, and in a format that allows them to respond so as to accomplish the mission. Figure 16 summarizes the importance of the interface between a human user and a robotic system.

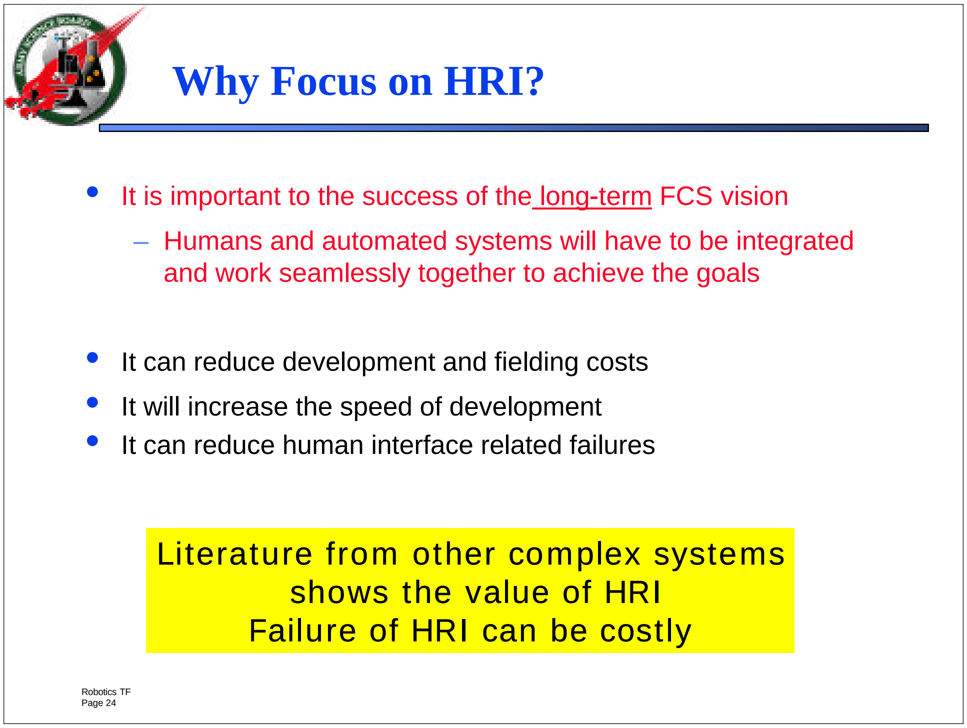

Figure 16. Importance of Human-Robot Interactions

4.3 THE VALUE OF HUMAN-ROBOT INTERACTIONS

We can only evaluate the value of human-robot interactions by examples from the field of Human Engineering (HE). HE looks at the issues of integrating humans into complex systems in an effective manner.

There are two major ways to illustrate the value of sound HE efforts. One is to show the negative results from lack of appropriate HE involvement, and the other is to demonstrate positive results of HE activities. The following sections examine the value of the HE effort from both perspectives.

4.3.1 Historical Problems from a Lack of HE Efforts

Lack of appropriate HE involvement in design can result in system shortcomings that require costly redesign, produce substandard system performance, or in extreme cases, precipitate system failures endangering life and equipment. Many problems found during testing and evaluation are evidence of the lack of a good HE effort during the design and development phase. While some of the problems are resolvable, it typically costs more to make these changes in the later stage of a program development.. Problems found during the operational phase are even more costly to resolve. Sometimes such problems are identified only after critical incidents. Two examples are provided to illustrate the problems that can occur when insufficient attention is paid to the HE aspects of design. The first set consists of several well-known disasters that, though they have multiple causes, resulted at least partly from lack of adequate HE. The second set is a sampling of specific lessons learned in a variety of HE-related areas. These examples are provided in the hope that future system designs will benefit from previous system design failures.

One of the technology areas in which systematic HE work is beneficial is the effective integration of humans with automated systems in flight-deck automation and glass-cockpit design. In this area a community of scientists, engineers, operators, and regulators works closely together to study, experimentally evaluate, and iteratively improve the interactions between pilots and the automated technology. Research shows that in general, improvements in automation significantly reduce pilot workload and stress. On the other hand, improper interactions and poor interface designs can lead to failures: “Since these aircraft [glass cockpits] were introduced in the early 1980s, hundreds of incidents and a few fatal accidents have occurred in which pilot-computer interface was a factor.” [AWST Jan 1995].

Some of the “few” accidents in which automation was a possible contributing factor are listed below.

- Boeing 707, Jamaica, New York, 1962
- Lockheed L1011, Miami, Florida, 1972
- Douglas DC10-30, Luxembourg, 1979
- Douglas DC-10-30, Boston, Massachusetts, 1982
- Douglas DC-10, New York, New York, 1984
- Boeing 747-SP near San Francisco, California, 1985
- Airbus 320, Mulhouse-Habsheim, France, 1988
- Airbus 320, Bangalore, India, 1990
- Boeing B767-300, Suphan Buri Province, Thailand, 1991
- Airbus 320, near Strasbourg, France, 1992
- Douglas MD11, Alaska, 1993
- Airbus A320 Warsaw, Poland, 1993.

4.3.2 Catastrophic Accidents

The failure to adequately consider human capabilities and limitations in system design can sometimes have disastrous consequences, as illustrated by the following three well-known incidents.

Downing of Korean Air Lines Flight 007

Soviet air-to-air missiles shot down KAL-007 on 1 September 1983, when it strayed into Soviet air space. A navigational error led the aircraft approximately 365 miles off course, placing it over Soviet military installations at Sakhalin Island. All 269 people on board perished after a 90-second descent into the Pacific Ocean. The most likely cause of the navigational error concerns the inertial navigation system (INS) installed in this large passenger aircraft. The aircraft had three INS systems: one primary system and two backups. Each INS could be programmed separately, or a “remote” mode could be chosen in which the crew programmed only the primary INS and the information was then automatically passed to the two backup units. To ensure that the proper coordinates have been placed in the system, the INS checks the primary INS coordinates against the coordinates entered into the two backup units. It is hypothesized that the crew, to save time and energy, chose the “remote” mode when programming the INS units and

incorrectly entered the flight path coordinates. This error would not have been detected when in this mode, because a copy of the incorrect coordinates would have been used to check the original incorrect coordinates. This INS was designed to reduce workload and stress to the aircrew. Unfortunately, the system was so automated that it caused inactivity, boredom, and complacency. Due to the defective interface of its INS, KAL-007 found itself off course and in unfriendly airspace, which led to tragedy [Stein, 1983; Malone, 1990; Time, 1992].

Three Mile Island Incident.

On 28 March 1979, operators at Three Mile Island, a nuclear power plant in Pennsylvania, made a series of mistakes that led to a near meltdown of the plant's reactor core. A series of equipment failures also contributed to this accident. The result was a release of approximately 1200 millirems per hour of radiation into the environment, forcing the evacuation of several thousand residents of the surrounding area. Fortunately, there were no deaths as a direct result of the incident. The near meltdown of the reactor occurred when a pilot-operated relief valve at the top of the pressurizer failed to close, resulting in the loss of a pressurizer steam bubble and the loss of reactor control system pressure and quantity. The indicator light on which the operators relied to determine the position of the relief valve led them to believe that the valve was closed, but the light was not displaying the actual system state—rather, it showed the presence of a signal commanding the valve to close. In other words, the operators believed the relief valve was closed when in reality the valve was open, despite the command to close. This belief led the system operators to conclude falsely that a leak had occurred, and they began to act accordingly. However, they continued to make errors that increased the volatility of the system, such as confusing reactor B with reactor A (a problem directly attributable to the control panel layout). Two hours later an operator who had recently arrived realized that the relief valve was at fault and initiated proper actions to correct the problem. In the end, an investigation by the Nuclear Regulatory Commission into the human factors aspects of the accident determined that "the human errors which occurred during the incident were not due to operator deficiencies but rather to inadequacies in equipment design, information presentation, emergency procedures, and training" [Malone 1990].

Crash of a Passenger Airliner into the Florida Everglades.

In 1972, a Lockheed L-1011 descended at night into the swamp of the Florida Everglades, killing all 99 passengers and crewmembers on board. The ensuing investigation by the National Transportation Safety Board (NTSB) revealed that one small, burned-out light bulb in the landing gear indicator set in motion a sequence of events that ended in a completely avoidable tragedy. More precisely, the response of the flight deck crew to the inoperative bulb ultimately hardened the last links in the chain of errors that led to the eventual crash of the aircraft. While in flight, each of the three crew members (flight engineer, first officer, and captain) fixated on solving the same problem, an aberrant "landing gear down and locked" bulb, while neglecting to notice that the autopilot had become disengaged. Quietly, while all crew members were attending to the same non emergency condition, the aircraft descended, under neither human nor automatic control, until it finally came to rest in the swamp below [NTSB, 1973].

4.3.3 Lessons Learned

The following lessons learned summarize in condensed form the experiences of users and managers of systems whose designers failed in some way to adequately consider human capabilities and limitations. It is often difficult to obtain detailed data directly related to such

problems, since these could be used to indicate an error or tarnish the image of a contractor. To avoid legal ramifications, the lessons learned are stated in very general terms, and references to specific defense systems and manufacturers have been omitted. In some cases, human engineering was involved late in the design process and the problems were turned into success stories. One major lesson learned is that costly engineering changes could have been prevented if HE had been involved earlier in the systems acquisition process. We present three examples.

Landing Gear Visibility at Night

Failure to design a helicopter landing gear so that it remains visible to the landing signal crew at night can result in a wheels-up landing, causing damage to aircraft, safety hazards to aircrew and ground personnel, and operational loss of a valuable fleet asset. [Department of the Air Force 1996].

Attitude Directional Indicator (with no Velocity Vector

Heads-up display without velocity vector indicators do not provide a flight path marker, leading to possible situational awareness problems for the pilot [Air Force HSI Office 1995.

Night-Vision Goggles and Exterior Lighting.

A failure to provide fleet aircraft with exterior lighting compatible with the use of night-vision goggles for night missions can result in mid-air collisions with aircraft that are not operating within the flight formation [Department of the Air Force 1996]. (See appendix D for more examples)

4.3.4 Benefits from Human Engineering

As with most worthwhile efforts, HE requires an investment of money and time to gain eventual savings, increased total system performance, safety, and user satisfaction. Typically, an investment in HE is relatively small compared to those in other system creation activities, while the return is relatively high (see Table 3).

Table 3. Example Benefits from HE

System Type	Investment ($)	Total Savings ($)	Time (Years)
Reconnaissance & Light Attack Helicopter	74.9M	3.29B	20
Attack Helicopter	2.3M	268.8M	20
Nuclear/Biological/Chemical Reconnaissance Vehicle	60K	$2–4M	l

Source: Booher [1997]

HE efforts strive to optimize a system to (1) permit operator and maintenance personnel to achieve the required performance levels; (2) minimize manpower, personnel and training requirements; (3) achieve the required reliability and effectiveness of personnel-system combinations; and (4) enhance operational safety by avoiding human error. These benefits can be seen in overall system and HE testing and evaluation reports. Success stories such as the following help illustrate the importance and value added of HE efforts.

Center High-Mounted Brake Lights.

In 1985, after extensive HE studies showing positive results, high-mounted center brake lights became standard equipment on all new passenger cars in the U.S. Vehicles equipped with the new brake lights are involved in 50% fewer rear-end collisions, and when an accident does occur, the costs of repairs are 50% less. It was estimated that 126,000 reported crashes would be avoided annually from 1997 on, resulting in savings of $910 million a year. These benefits stemmed from a $5 million investment in HE [Hendrick, 1996].

Redesign of Aircraft Throttle Module

An oversensitivity problem (an unacceptably large output in response to a small input) was discovered in the use of the throttles of a large transport aircraft during aerial refueling. After engineers unsuccessfully redesigned the throttles without HE input, the HE group was asked to develop a solution. The HE practitioners collected and analyzed data and identified critical component failures. They worked with designers to modify the throttles by reducing the spring force, smoothing the cam action, and adding helper handles. The resdesign was greeted with overwhelming pilot acceptance [Air Force HSI Office 1995].

Modification of a Manufacturing Facility

In the first year, following an HE evaluation and modification of a manufacturing facility, worker's compensation losses dropped more than 75%, from $400,000 to $94,000. The changes that resulted from this HE evaluation saved the manufacturer $1.48 million in the period 1990–1994 [Hendrick 1996].

Transceiver Operator Panel

Sound HE involvement often goes unnoticed because of the flawless way a system operates. A transceiver operator panel for the control of an airborne computerized communications sending and receiving processor was designed according to HE principles. A task analysis fleshed out six major system requirements, and fit the system into an existing slot on the flight deck. The design was integrated into the operator's concept of operation so well that upon first questioning during T&E, the field-test engineers could not recall using the system at all [Shafer 1976].

4.3.5 The Pervasive Impact of Windows and GUIs.

The previous examples in this section have focused on the problems that occur when user interaction design is not done in a rigorous or systematic manner. The computer industry presents one significant example of the positive value of developing interactions and interfaces in an organized manner—the development of graphical user interfaces (GUIs), leading to the present day Windows™ operating system.

In the early sixties, the US Air Force funded a series of research contracts for the examination of human interactions with time-shared computer systems that were then starting to come into being. One of these contracts was to a visionary computer scientist, Douglas Englebart, who was then with the Stanford Research Institute in Menlo Park, CA. Doug focused his energies on understanding how humans would interact with computer information, and in doing so, developed concepts such as multimedia, hypertext, windows, icons, and the computer mouse. In the fall of 1968, Doug demonstrated the first "personal computing" platform with a mouse controlling a networked computer system with hypertext linking, real-time text editing, multiple windows, and teleconferencing.

These concepts, evolving through the lineage of Xerox, and Apple, became widely adopted as the preferred mechanisms for interacting with computer information. Arguably, the windows-type interfaces map readily into the cognitive models that underlie common office actions such as filing information, searching, and indexing. It is this mapping that makes windows-type interfaces "intuitive". Our challenge to the robot human interaction community can be summed up in one short sentence: "What is the analog of the desktop metaphor, in the field of robotics?"

We feel that if such an intuitive model could be devised, it would provide a significant boost to the usability, and hence deployment of robots in the Army.

5 PANEL FINDINGS

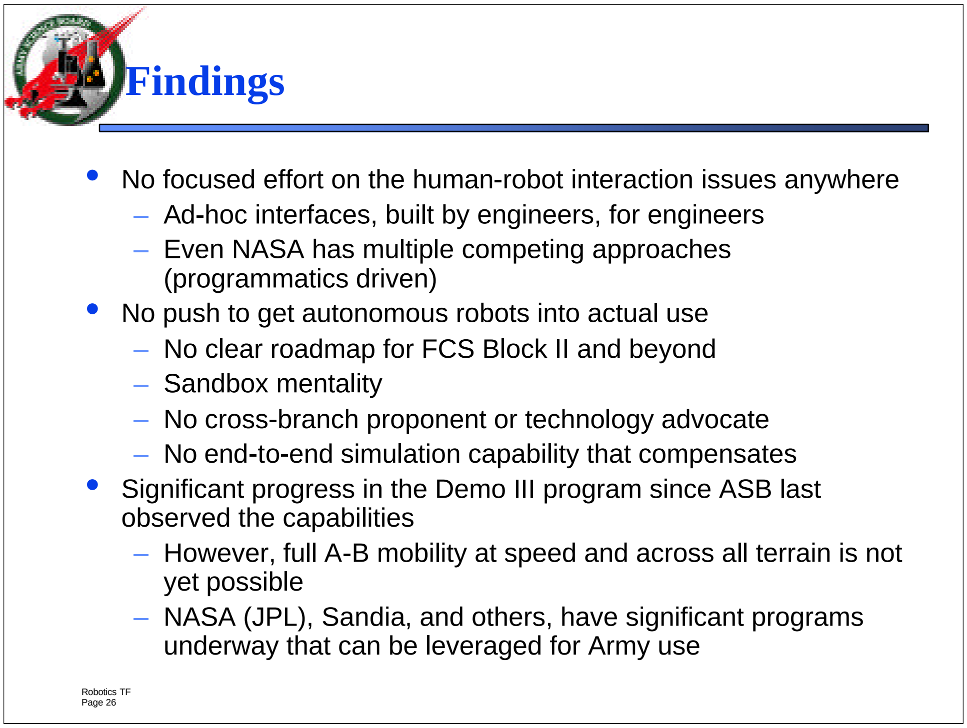

Figure 17. Findings

5.1 SIGNIFICANT ADVANCES IN FUNDAMENTAL ROBOTICS TECHNOLOGY

Significant progress has been made in the Demo III program since the ASB last observed the capabilities. The final capabilities demonstration at Fort Indiantown Gap in October 2001 showed a convincing capability of unmanned, supervised autonomous systems to perform a meaningful set of RSTA tasks. Although full A-B mobility at speed and across all terrain is not yet possible, ground vehicle robotics technology has matured sufficiently that useful military systems can be fielded. Robotic ground vehicle development has reached a point where user input is needed to carry the work forward to fully useful robotic combat systems. The Real-time Control System (RCS) is one of the best control system architectures to achieve greater unmanned vehicle autonomy. The Army Vetronics Technology Integration (VTI) program and the associated Crew Automation Testbed/Robotic Follower (CAT/RF) Advanced Technology Demonstration (ATD) program are starting to address the issue of integrating Demo III mobility and perception capabilities into a transitionable system.

5.2 NO SYSTEMATIC STUDY OR APPLICATIONS OF HUMAN-ROBOT INTERFACE DESIGN

There is no systematic application of basic principles to the matter of human-robotic interfaces. All robotic systems have human interfaces, which leads to an assumption in the

research community that the problem is being addressed. Most interfaces that we observed (Army programs, NASA programs, etc.) have interfaces designed primarily by robotics engineers for their own use. Even interfaces (such as those on the NASA space programs) that have been designed by committees with end-user participants have not evolved according to a systematic hands-on analysis of the actual use of the interfaces in real-world conditions. Other technical areas that have systematically applied HE processes in the past (such as flight deck automation) have reported significant measurable value from the application of systematic techniques.

There is a lack of systematic analytical and/or experimental work to identify the combat functions and tasks that could have the highest payoff from the use of unmanned vehicles; and to define the soldier interface design required for unmanned vehicles that will perform combat functions and tasks. This is especially true with regard to telemanaged systems

Every project approaches the human-robotic interface problem in its own way. The usual programmatic drivers for this are principal investigators who are focused on the core robotic or platform technologies rather than interfaces (for example, Demo III's main focus is on developing perception technology and not on the robotic system per se); the lack of a systematic understanding of the goals of the system and the tasks expected to be carried out by the elements of the system (including the human elements); and the lack of hands-on experience with the existing robotic systems in the field to catalog and document interaction needs. Acceptable metrics for human-robot interfaces are also lacking.

5.3 DISCONNECT BETWEEN END USERS AND DEVELOPMENT PROCESSES

Basic robotics technology has progressed to where it is possible to incorporate some elementary ground robotics capabilities into FCS Block I if the acquisition system were structured to move technology rapidly into the field. Robotic ground vehicles still do not have a "sponsor" in the way that aviation, trucks, guns, missiles, and tanks do. To be successful, FCS program management has to be able to find needed, useable military or commercial technology and force its rapid maturation, but the "normal" processes of the acquisition system cannot deliver the needed technology in a timely fashion. The fielding of existing developmental robotic ground vehicles for training purposes also would speed up combat development work for the FCS, but there does not appear to be any clear path by which the (robotic vehicle) work being done within the Army R&D community can find its way into the FCS development program.

The Army acquisition system appears to be disconnected at every transition point in the developmental process. The system is focused on formalism, on organizational structure, on funding categories—and on a zero defects philosophy that is totally intolerant of fielding less-than-perfect equipment. An output-oriented, field-and-upgrade approach is at the heart of the spiral development concept, which focuses on moving new technology through the developmental process and into the field as quickly as it can be made useful. A recent *Defense News* article points out, however, that Congress does not want to buy anything until it has been completely tested and proven [Kaufman 2002]. In that regard, the Army Acquisition System is in step with Congress, which may be very unwilling to accept the notion of spiral development. The Army often is accused of stovepiping development on the assumption that this is a bad way to manage R&D, when the perceived stovepipe development was actually quite logical and served very well. Stovepiping was an effective way to develop the equipment the Army needed when there was relatively little technology crossover between the systems concerned. The large systems

developed in the 1970s and 1980s—M1 Abrams, HMMWV, HEMTT, Apache, Blackhawk, etc.—were products of that type of development, as were their many predecessors developed from 1940 to1970.

Over the past 60 years, however, as technology became more complex and system costs rose astronomically, local control over the development process has continually devolved toward a centralization of decision-making in the Department of the Army (DA) and the DoD. At the same, time much formerly in-house Army R&D work has migrated to industry, with a consequent degeneration of government "engineering muscle" into "bureaucratic gristle." The time needed to develop and field a new major item has at least doubled since 1960. There still are many pockets of solid technical capability in the Army system, some of which we encountered in the course of this study. But, like a species being driven toward extinction by piecemeal habitat destruction, they increasingly are isolated from the interaction with major system developments that is essential both for them to contribute and to survive.

The FCS development program forces all of the Army Acquisition System's faults and problems out into the open. It demands the rapid fielding of new technology, and, being a "system of systems" it chops across the "stovepipes." The Army's response is to bypass FCS development by turning to industry for a "lead system integrator" (LSI) to integrate the disparate technologies involved into a coherent combat system. It remains to be seen how well this approach is going to work. The gold standard for such a development program is the Navy's 1950s Polaris program, a tough standard to meet with regard to both quick response and useful output. The Army materiel acquisition organization is highly compartmentalized, and putting together a project management structure that can quickly mobilize its resources for the FCS will be challenging at best. Technologies such as UGVs may get lost in the shuffle. In the course of its deliberations over the past 10 months, the Human-Robot Interface panel saw considerable reason to believe that is a likely outcome for the very promising robotics work currently going on in the Army laboratories and Research, Development and Engineering Centers (RDECs). The FCS program management structure must be set up to prevent this outcome since the FCS cannot become a successful fighting system without its robotic subsystems. In fairness, however, we must point out here that it is easier to apply spiral development and still exercise adequate configuration control over a fleet of less than 50 large, very expensive capital ships [none of which are ever exactly alike, anyway!] than it is to control the configuration of a fleet of tens of thousands of combat and tactical vehicles. Anyone who has ever dealt with serial production and maintenance of equipment in the field should be a serious believer in rigorous configuration control. This is one of the fundamental weak points of the spiral development approach. In the Army, spiral development could easily lead us to the German Werhmacht's WWII problem of ground vehicle populations that were riddled with more or less undocumented running production changes, to mention only one problem. Modern computer systems should enable us to cope with spiral development today, but no one should think it will be easy or foolproof.

The FCS concept of a system of manned and unmanned vehicles, ground and air, is not new. Dr. James Albus of NIST[7] proposed the basic idea at the start of the 1980s in an address to an ADPA Combat Vehicles Conference. Dr. Albus referred to the concept as a system of "swarm

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[7] NIST: National Institute of Standards and Technology; ADPA: American Defense Preparedness Association.

vehicles": the unmanned air and ground vehicles in the swarm would both protect the manned control vehicle at the center of the swarm and serve, collectively, as its primary weapon. He was not the only person to suggest this general approach to future combat vehicles.

W. J. Whelan [1982] laid out a novel concept for a future fighting vehicle system of small robotic fighting vehicles under the direction of a larger manned vehicle. The concept, while perhaps prophetic, realistically was not testable at the time it was proposed, nor was it possible then to predict with credibility when developments in computing technology might make it possible to build such a system. When H. H. Dobbs proposed a similar approach [1993] the technology picture had cleared considerably, and the explosive growth of computational power over the proceeding decade pointed to such military robotic vehicle systems becoming practical in the foreseeable future. The article, however, received little comment. At that time the Armor community was still in the afterglow of its brutally decisive success in Operation Desert Storm. Not one U.S. tank crewman was lost to enemy action during the 100 hours of the Desert Storm land battle, while literally every Iraqi force that tried to fight them was totally destroyed and suffered enormous loss of life. The Army focus then was on a "Super M1" as the future successor to the already dominant M1 Abrams series of Main Battle Tanks (MBTs). The ASB Tank Modernization Study of 1995-1998 reflected that focus. Robotic vehicles were discussed only in an appendix. However, military robotic vehicle research did continue throughout the 1980s under the direction of the DoD land warfare systems specialists and DARPA. Congress created the DoD Joint Robotics Program (JRP) in 1989 to consolidate all such efforts. The Unmanned Ground Vehicle/Systems Joint Project Office (UGV/S JPO) was established at Redstone Arsenal in Huntsville, Alabama to work with ground robotic vehicle systems. Members of this panel were briefed on some of their work during our visit to the U.S. Army Aviation and Missile Command (AMCOM). The Board on Army Science and Technology (BAST), an element of the National Research Council, stated in its 1992 report on the Army of the 21st century that "the core weapon of the 20th century has been the tank. The core weapon of the 21st century may well be the unmanned system operating mostly under computer control [i.e., autonomously] with human supervision."

The Demo III work that some study group members observed at Fort Indiantown Gap began in 1998 [Bornstein and Shoemaker 1998]. At that point in time management of the work shifted from the DoD and DARPA to the Army, and ARL and the U.S. Army Tank Automotive and Armaments Command (TACOM) became involved. The involvement of TACOM, which is responsible for the development of vehicle and armament systems for the Army was a clear indication that robotic ground vehicles were approaching the point of practical application in the field.

By the end of the 1990s it also had become possible to predict with reasonable accuracy when a given level of computational capability would become available at a chosen cost level. The Impact Matrix for Computational Technology [Dobbs 2002] shows such estimates at nominally current PC price levels. Professor Moravec, one of the most knowledgeable people working on robotic intelligence and sensing, estimates that machines will reach human-level speed (10^8 MIPS) by the year 2040 [Moravec 1999]. Current supercomputers already process data at about 4 ? 10^6 MIPS, and the goal of the IBM Corporation Blue Gene project [DeCusatis 2001], first announced in 2000, is to build a supercomputer with a speed of over 10^{10} MIPS by 2005, one hundred times Professor Moravec's estimate of human-level speed. This supercomputer will need

approximately 10^{13} bytes of memory. The price of supercomputer speed usually falls to PC levels by about 20 years after its introduction; the price of computer memory capability has always closely followed that of computational speed. Professor Moravec's estimates of the time when robots will reach human mental capability thus may appear conservative. However, note that although *computational speed and memory capacity are necessary conditions for intelligence, they are not necessarily sufficient conditions!* No one yet knows what the sufficient conditions are. A great deal of work also remains to be done in the areas of sensors and the interpretation of their outputs before fully autonomous machines become practical.

Nevertheless, the U.S. military is moving strongly toward robotic vehicle systems for many missions, including combat, in the near to mid term. Congressional pressure to move in that direction also has developed [Wolfe 2000]. Army leadership now appears to understand the necessity of robotic vehicle systems, a capability inherent in the FCS concept. Whether the Army in the field understands yet is less clear, and whether the acquisition system can successfully develop and field a fightable initial version of the FCS in the appropriate time frame is open to question. Fielding even one of the robotic units derived from the Demo III work with the Block I version of the FCS would both improve the system's survivability and let the soldiers begin to learn to use the FCS in the ways that will make it a successful weapon system. The HRI panel believes that the Army can accomplish this goal.

For the present (until the FCS comes on the scene), the panel believes that, with a minimum of changes, the Demo III robots they observed in November at Fort Indiantown Gap are suitable for issue to troops in well-defined environments for testing and training. These activities would provide essential feedback to both the FCS developers and the combat development community and would ensure that the FCS was far more capable when initially fielded. The benefits of this approach should greatly outweigh the moderate cost of the equipment involved. The interim brigades might be the best choice for the initial fielding of this equipment.

6 PANEL RECOMMENDATIONS

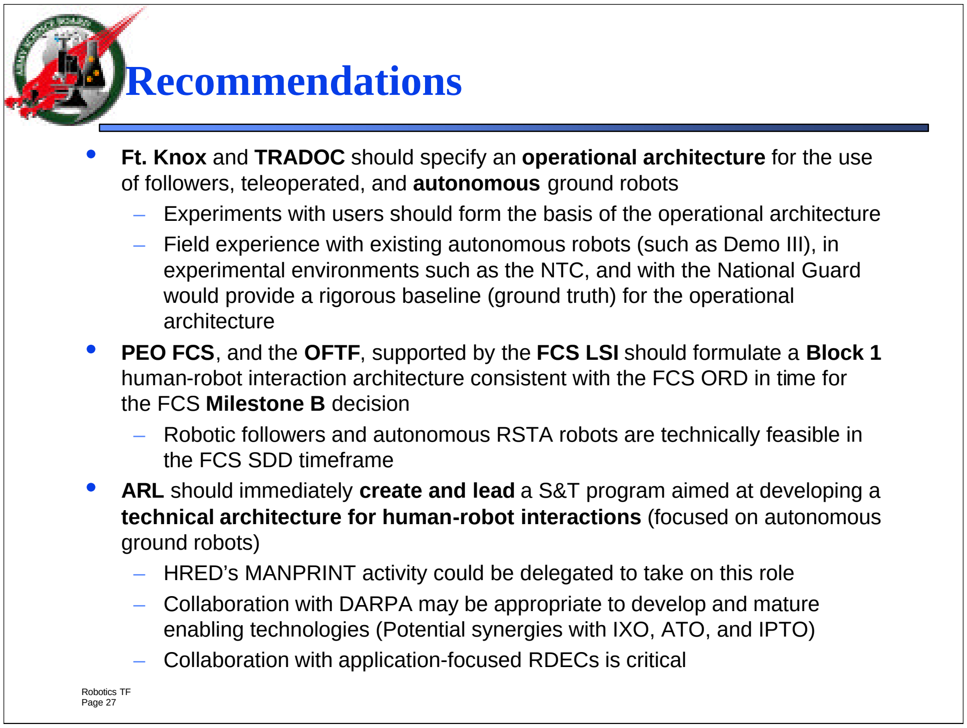

Figure 18. Recommendations

6.1 SUMMARY RECOMMENDATION

The panel recommends that the Army move rapidly to create a strong, technology focused program for understanding and developing the technologies for human robot interactions, with particular emphasis on autonomous ground robots. We recommend that such a program be grounded in well-articulated operational needs, and be oriented towards the transformation and objective force requirements. The proposed efforts should augment and build on the successful robotic ground vehicle work that has been done in the Army laboratories (particularly, ARL) and RDECs—most specifically the Demo III and related ground robotics programs.

To this end, we make three specific recommendations.

6.2 DETAILED RECOMMENDATIONS

1. **Ft. Knox** and **TRADOC** should specify an **operational architecture** for the use of robots, particularly followers, teleoperated systems, and **autonomous** vehicles.

   - To be useful, the operational architecture must be baselined with experimental data gathered in operationally relevant scenarios, and in realistic operational environments.

- To this end, we suggest that the Army apply additional resources to initiate accelerator low rate initial production (LRIP) fielding of the Demo III RSTA robots with organized feedback to the supporting R&D programs, and constant upgrades to the fielded robots—total deliberate integration on a real-time basis of (1) the material development process, (2) the combat development process, (3) troop training, and (4) lessons learned from combat. The Human-Robot Interface panel is not aware that the Army has done this before except on a very limited basis during wartime. In this environment the difference in the nature of robots from previous equipment should surface.

- Research should continue in improving the core robotic technologies (particularly perception, navigation, and mobility). The most important aspect of a robotic weapon system, its (obviously still limited) ability to "think", will improve in the field, due to its "experiences" in dealing with its environment (soldiers and missions) and to relatively low-cost software and hardware upgrades to its ability to learn.

- Focus robotic R&D on making the following improvements in robot capability and self-sustainment ability

    1. Increased temporary memory (RAM) and processor speed (a factor of 10? is available now)
    2. Permanent memory (must be rugged)
    3. Sensory capability to "see" and understand
    4. World model software (its local world: terrain, weather, mission execution, "its soldiers," etc.)
    5. Ability to manipulate its environment, support its own needs
    6. Ability to communicate with humans, electronically and verbally
    7. Improved automotive capability

2. **PEO FCS**, and the **OFTF**, supported by the **FCS LSI** should formulate a **Block 1** human-robot interaction architecture consistent with the FCS ORD in time for the FCS **Milestone B** decision

    - Having a user community "pulling" the autonomous robotics technology is an invaluable motivator for the future development of the field. As we have indicated in the report, autonomous operation is a key need for FCS. FCS and the Objective Force Task Force are therefore, the most appropriate "customers" who should drive for technology adoption, and define an architecture for human-robot interactions.

3. **ARL** should immediately **create and lead** a S&T program aimed at developing a **technical architecture for human-robot interactions** (focused on autonomous ground robots)

   - HRED's MANPRINT activity could be delegated to take on this role. ARL should establish an R&D program to systematically review the possible forms of human-robotic interfaces and the work that has been done in this area, and develop guidelines for the development of future military robotic systems. The program should consist of an analytical/experimental effort to:

     A. Identify the combat functions/tasks that could benefit most from the application of unmanned vehicles

     B. Determine the interaction class that best fits the identified combat functions and tasks that have the highest payoff if unmanned vehicles are used

     C. Provide design guidance for the unmanned vehicle and the operator control and display interfaces that will provide the desired operational capability

   - Collaboration with DARPA may be appropriate to develop and mature enabling technologies (Potential synergies with IXO, ATO, and IPTO)

   - Collaboration with application-focused RDECs is critical.

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Appendix A: Participants List

PARTICIPANTS LIST

ARMY SCIENCE BOARD 2001 AD HOC STUDY
HUMAN ROBOTICS INTERFACE ISSUES

ASB Panel

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SRI International

Dr. Herbert Dobbs
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Torvec, Inc.

Dr. John Blair
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Assistant Secretary of the Army for Acquisition, Logistics and Technology [ASA(ALT)]

Appendix B: Acronyms

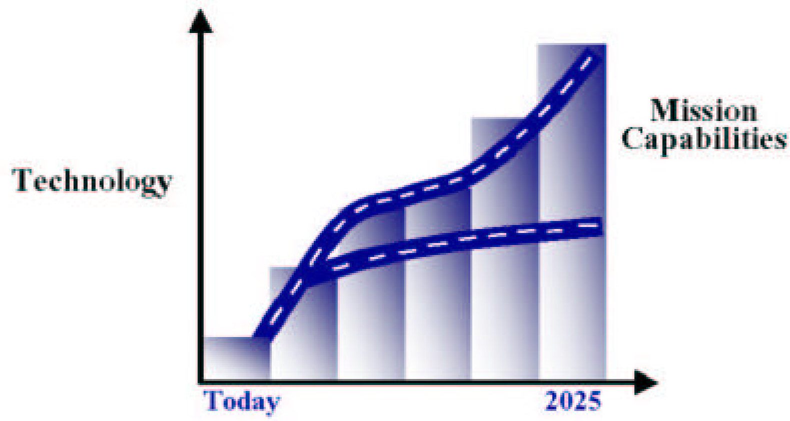
ADI	Attitude Directional Indicator
ADPA	American Defense Preparedness Association
AMCOM	Aviation and Missile Command
ARL	Army Research Laboratory
ARL-XUV	Army Research Laboratory—Experimental Unmanned Vehicle
ASB	Army Science Board
ATD	Advanced Technology Demonstration
ATO	Advanced Technology Office (DARPA)
BDA	Battle Damage Assessment
BAST	Board on Army Science Technology (National Academies of Science, Department of Military Science and Technology)
C4ISR	Command, Control, Communications, and Computers, Intelligence, Surveillance and Reconnaissance
CAT/RF	Crew Automation Testbed/Robotics Follower
DA	Department of the Army
DARPA	Defense Advanced Project Research Agency
DoD	Department of Defense
FCS	Future Combat System
GUI	Graphical User Interface
HE	Human Engineering
HF	Human Factors
HFE	Human Factors Engineering
HRI	Human-Robot Interface
HSI	Hyperspectral Imaging
INS	Inertial Navigation System
IPTO	Information Processing Technology Office (DARPA)
IR	Infrared
IXO	Information Exploitation Office (DARPA)
JPL	Jet Propulsion Laboratory
JPO	Joint Program Office
JRP	Joint Robotics Program
KAL	Korean Air Lines
LADAR	Laser detection and ranging

LRIP	Low-rate initial production
LSI	Lead System Integrator
MAV	Manned Aerial Vehicle
MBT	Main Battle Tank
MIC	Methyl isocyanate
MIPS	Million Instructions per Second
MMWR	Millimeter Wave Radar
MOUT	Military Operations in Urban Terrain
MPRS	Man-Portable Remote System
MPT	Military potential test
NASA	National Aeronautics and Space Administration
NBC	Nuclear, Biological and Chemical
NIST	National Institute of Standards and Technology
NRC	National Research Council
NTC	National Training Center
NTSB	National Transportation Safety Board
OFTF	Objective Force Task Force
OFW	Objective Force Warrior
ONR	Office of Naval Research
OPFOR	Opposing Forces
OSD-ATL	Office of Secretary of Defense – Acquisition, Technology and Logistics
PC	Personal Computer
PEO	Program Executive Office
PI	Principal Investigator
Psig	Pounds per square inch gauge
R&D	Research and Development
RAM	Random access memory
RCS	Real-time Control Systems (other contexts, Radar Cross Section)
RDEC	Research, Development, and Engineering Center
RSTA	Reconnaissance, Surveillance, and Target Acquisition
S&T	Science and Technology
T&E	Test and Evaluation
TACOM	U. S. Army Tank Automotive and Armaments Command
TIC	Tactical Information Coordinator
TMR	Tactical Mobile Robotics (DARPA Program)

TOR	Terms of Reference
TRADOC	Training and Doctrine Command
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
UGCV	Unmanned Ground Combat Vehicle
UGV/S	Unmanned Ground Vehicle/System
UMV/S	Unmanned Vehicle/System
VTI	Vetronics Technology Integration
WITS	Wide-area Telerobotics Systems

Appendix C: Army UGV Roadmap

Unmanned Ground Vehicle Technology Roadmap



DRAFT

Prepared for the Army
by the Task Force on the Future of
Unmanned Ground Vehicles

July 2001

Task Force on the Future of Unmanned Ground Vehicles

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Cover Illustration: The intent of the illustration on the cover is to evoke the objective of a technology roadmap: to identify and clarify the relationship between the need for specific technological capabilities to meet an organization's goals, and the evolution of science and technology that will enable these capabilities. This Unmanned Ground Vehicle Roadmap makes explicit the link between the anticipated Army missions defined by the *Objective Force* and the evolution of science and technology that will be required to support these missions.

Table of Contents

The Unmanned Ground Vehicle Roadmap was developed to provide a structure for organizing S&T programs in support of Army missions for a period of more than 20 years. The complexities of the anticipated missions, the environments in which they will be carried out, and the nature of the UGV technologies themselves have dictated that the Roadmap address the Army's needs at two distinct levels of detail. For near-term missions and consequent S&T needs, the Roadmap provides substantial detail (see Section 2.1). For mid- and long-term missions and needs (sections 2.2 through 2.5), the Roadmap's recommendations are broader, as is appropriate, given the uncertainties in how both the Army's missions for UGVs and robotic S&T will evolve.

1.1.4 A Word about Autonomy

The UGV user community and the UGV R&D community each commonly use the word "autonomy" in discussions of goals, as in "today we are at teleoperation and sometime in the future we'll be at autonomy." Although the word is useful as shorthand for conveying a very general goal, its fundamental ambiguity creates obstacles, both for those who would clarify what capabilities are needed and for those who would determine what research to pursue.

Why does the community care about mobility—autonomous or otherwise? Consider a commonplace analogy: a trip to the store to shop for groceries. Mobility is the means by which one gets to the grocery store, however the value-added part of the trip is not the drive to the store but what happens in the store. Most Army applications envisioned for UGVs are similar in that the value-added part of a mission comes at the end of the journey. (In this, UGVs are of course no different from manned forces.) Thus there is great motivation to develop the capability to carry out the non-value-added portion of missions with high effectiveness.

How did the community come to the conclusion that vehicles need autonomous mobility? A long history of experimentation shows that *remote control* of vehicles—operation with no visual input to the remote operator—is ineffective. Furthermore, even *teleoperation*—when visual input is provided—is not effective, especially when the UGVs must keep pace with a manned force moving cross-country. There are not yet agreed-upon, proven, and effective means of implementing the non-value-added portion of most important missions: getting the UGV to a point where it can carry out its mission objective. Yet, without the means to perform the non-value-added portion of the mission effectively and with confidence, the Army will not be able to fully achieve its expectations for UGVs.

Why is autonomous mobility so hard? Consider another analogy: the re-entry vehicle on a long-range missile. The U.S. has demonstrated vehicles that can sense atmospheric disturbances and adjust their trajectory to ensure high end-point accuracy. Conventional wisdom holds that effective UGVs must have a comparable characteristic: they must know where they are, where they want to get to, and how to adjust their trajectories for unexpected disturbances along the way.

For various reasons, including more difficult "disturbances" and vastly more important effects of "clutter" on the sensors, this is a much more difficult task for UGVs than for re-entry vehicles.

What can be done about this? To begin with, discussions of autonomy are fraught with difficulty because autonomy has not been defined in engineering terms. Although the UGV community generally subscribes to the idea that there are differing levels of autonomy, without engineering definitions the user community cannot effectively estimate the value of achieving various levels. And the R&D community cannot effectively describe what levels are possible. As a result, autonomy by itself does not provide significant assistance in choosing priorities from among many potentially relevant areas of R&D. The objective of the first recommendation of this Roadmap is to cut the Gordian knot of autonomous mobility.

To compound the problem, mobility is not the only UGV system function that requires more autonomy. Brief descriptions of other functions are provided below; the related needs are fully dealt with in the recommendations of the Task Force.

- **Autonomous Mobility** is a key capability. Although there are many opinions about the levels of autonomy that are required for effective mobility, there is little argument that significant advances are needed in the abilities of UGVs to get from one point to another with little or no human help along the way. If UGVs are to emerge from their current situation of niche applications, additional autonomy of mobility is critical. For this reason a significant portion of the roadmap is concerned with accelerating development of autonomous mobility.

- **Coordinated Action of Mission Package and UGV.** Today little or no research is focused on the capabilities necessary to coordinate the actions of mission packages and UGVs. As an example of the need, an autonomously mobile UGV with a functional Automatic Target Recognition (ATR) system will be useless if the UGV is unable to ensure good lines of sight for the ATR.

- **Autonomous Cooperation Among UGVs.** The missions identified for the longer term will require self-generated cooperation among teams of UGVs. This will require greatly enhanced communication and decision-making capabilities, for example the information sensed by one UGV can be used to define the actions of another without requiring the input of a remote operator.

The bullets above call for a more systematic approach to the development of autonomy of differing types. Resonances of this theme will be heard throughout the remainder of the document.

Appendix D: Examples, Lessons Learned, and Benefits

Downing of Iranian Air Lines Flight 655 (IAL-655).

On July 3, 1988, the U.S.S. Vincennes shot down a commercial airliner over the Persian Gulf. These circumstances, combined with the fact that an Iranian F-14 had been observed taking off from an Iranian military base in the same general location and at approximately the same time as the commercial airliner, led to the accident. With such intense expectations of an attack, and given previous observations allowing for the possibility of an F-14 cloaking itself as a commercial airliner, the crew was falsely led to believe they were under attack. The official investigation of the incident by Admiral Fogarty used the phrase "scenario fulfillment" to describe the tactical information coordinator’s (TIC’s) distortion of the situation. The investigation states, "Stress, task fixation, and unconscious distortion of data may have played a major role in this incident." (Based on Malone, 1990)

The accident occurred in part because a TIC mistakenly reported the aircraft as descending over the ship, based on the seaman's perception of the information gathered from his display, when in actuality the aircraft was ascending. Two other crew concurred with the TIC's assessment of the situation. To understand why this error happened, we must examine the events leading up to this incident. The accident is a classic example of the influence of expectancy in causing human error. Already in a stressful environment, naval personnel in the Gulf were told to expect an attack from the Iranians on Independence Day. In addition, specific warnings were issued concerning possible attacks from Iranian F-14 Tomcats. From June 2 - July 2, 1988, there were 150 challenges issued by warships to aircraft. Of these, 83 percent were to Iranian military aircraft (7 of which were F-14s), while only 1.3 percent were issued to commercial aircraft. Moreover, Iranian F-14s were previously observed flying commercial traffic routes for cover, emitting radar squawk signals of commercial aircraft in tandem with their military squawk.

Industrial Accident at Union Carbide.

On December 2, 1984, the accidental release of a toxic chemical from a Union Carbide subsidiary in Bhopal, India, killed at least 2,500 people (official count) and quite possibly as many as 10,000. In addition, over 150,000 people (from a population of 672,000 in this urban area) sought medical attention resulting from the accident. The incident occurred at night when the pressure relief valve blew out on a tank containing 45 tons of methyl isocyanate (MIC), releasing its contents and bathing the city of Bhopal in suffocating fumes. MIC is a highly volatile, unstable, flammable chemical that becomes a gas at approximately 100 degrees F and is highly reactive with water at any temperature. In this accident, the MIC in the tank became contaminated with water when the connecting lines were flushed during a routine maintenance operation. Within a period of less than two hours, the pressure in the tank had risen from its normal acceptable level of between 2 and 25 psig to well in excess of 55 psig, and the temperature had soared to at least 392 degrees F, causing the relief valve to open. The accident was attributed to human error caused by carelessness, poor training, and improper maintenance, as well as design shortcomings in the control room. Control room instrumentation supplied no record of previous values for important system parameters such as tank pressure to supply a historical trace for an operator who was taking over a shift from another (the accident occurred within a few hours of shift change). The upper limit on the displays for the tank temperature and pressure gauges was too low to adequately reflect the conditions in the tank (for example, the pressure gauge topped

out at 55 psig). The tank temperature display was not even located in the control room. In Bhopal after the accident, Union Carbide's chairman, Warren M. Anderson, expressed his concern for the loss of life, but maintained that the "safety standards in the U.S. are identical to those in India…. Same equipment, same design, same everything" (Casey, 1993). Unfortunately, that was part of the problem. The designers of the plant did not anticipate the cultural differences between the operators in India and their American counterparts. Nor did they take into consideration the fact that requiring the Indian operators to keep their logbooks in English, a second language for the Hindi personnel impeded the transfer of information between operators. Finally, two safety mechanisms that could have contained the accident failed. The neutralizing soda scrubber system was grossly inadequate; it was designed to absorb 190 pounds of gas per hour at 15 psig and 95 degrees F, but, at the time of the accident, the MIC was flowing at 40,000 pounds per hour at a temperature of over 392 degrees F. The flare tower that could have harmlessly burnt off the gas was not in operation. (Based on Malone, 1990; Casey, 1993)

Lessons Learned

Effects of joint range of motion limits on strength.

When the angle of a fully deflected aircraft rudder/brake pedal is beyond the limit of ankle mobility, the pedal will seem to have excessive resistance. In addition, this will prevent the pilot from fully utilizing the brakes of the aircraft. (McDaniel, 1998)

Component accessibility.

Failure to design aircraft components and equipment for easy accessibility causes excessive maintenance time for repair and decreased aircraft availability. (Department of the Air Force, 1996)

Cross-connected hydraulic lines.

Inadvertent cross-connection of hydraulic lines can easily occur when similar fittings are used for all lines, leading to extremely high human and equipment cost. (Department of the Air Force, 1996)

Command ejection option.

Lack of a command ejection option in a multiple-ejection-seat system can have two major negative effects: seats can collide because ejections are not coordinated; and one or more people may be left within the vehicle if they are unable to eject themselves. Either of these situations could result in loss of life. (Department of the Air Force, 1996)

Cargo-loading procedures.

When a winch operator loading cargo aboard an aircraft cannot see the cargo being loaded and does not have communications with the rest of the loading crew, safety is adversely impacted. (Department of the Air Force, 1996)

Overhead power lines and tall vehicles.

It is important to identify overhead hazards such as low power lines when planning and organizing work involving tall vehicles. Without proper identification of workplace hazards, the ability to minimize exposure to and protect personnel from hazards is significantly reduced. (Dept. of Energy, 1998)

Tactical altitude director system audio alarms.

When a low-altitude warning system sounds frequent false alarms, pilots become accustomed to the audio alarm and tend to ignore it. This can result in loss of the aircraft and aircrew through failure to respond to a valid alarm. (Department of the Air Force, 1996)

Life-raft deployment.

Life rafts not properly designed for quick and easy deployment can result in death to passengers and crew. (Department of the Air Force, 1996)

Human error in aircraft accidents.

Studies of commercial jet aircraft accidents attribute over 70 percent of accidents to crew error. (BOEING, 1993)

Benefits from HE

Nuclear/Biological/Chemical Reconnaissance Vehicle.

Redesigning interfaces utilizing subjective workload assessment, this system, originally requiring a four-member crew, was successfully reduced to three members. As a part of crew risk reduction, HE design principles enabled incorporation of standoff detection capability, thereby reducing exposure risk to crewmembers. In addition, HE involvement in overall system design integration allowed for considerable reductions in maintainability costs. (Booher, 1997)

Forward Area Artillery Resupply Vehicle.

During the beginning stages of system development, subjective workload analysis and computer modeling were used to determine optimal vehicle crew size for maximum mission performance. During the T&E phase of the design process, task analysis, and field observation techniques were utilized to identify critical areas of interaction between warfighters, equipment and environment during battle scenarios. Throughout the course of the project, these HE principles targeted key issues that were subsequently resolved by the design team leading to a more effective product. (Booher, 1997)

Transport aircraft redesign to accommodate parachutists

A joint Air Force-Army working group helped redesign the fuselage and door position of a large transport aircraft using HE principles to improve the airflow for parachutes. The vehicle is now considered the best aircraft for parachute jumping. (Air Force HSI Office, 1995)

Screen display redesign.

The CRT screen display used by the directory assistants at a regional telephone company was reconfigured in keeping with HE recommendations. After the redesign, the average time to process a call dropped by 600 milliseconds. This reduction saves the company $2.94 million a year across the five-state region served by the system. (Hendrick, 1996)

Training system redesign.

At the same telephone company, HE was applied in redesigning the systems used to train directory assistants. These revisions reduced the time needed to train an operator from five days to one and a half days. (Hendrick, 1996)

Shoulder-launched missile system.

A shoulder-launched missile system with challenging operational requirements received

extensive human engineering during its concept, design, test, and fielding, closely following the tasking in Section 4. Not only did it meet operational requirements, but also the design of the user-system interface and operational procedures enabled what might have otherwise been a complicated system, to facilitate effortless field use by third-world freedom fighters. Its original critics now praise the system for its simplicity. (Reed, 1988)

Gunship aft-scanner workstation redesign.

Because gunship aft-scanners (who look for missile launches and other threats from the tail of their aircraft) had to remain in an "unnatural" prone position for hours over hostile territory, they suffered back and neck pain. To remedy this problem, HE practitioners identified alternative design solutions for the aft-scanner workstation. The program office was able to fund several of these recommendations. As a result of the HE effort, weight distribution, body posture, positioning for mission tasks, functional reach, and external visibility were all improved, and neck and back pain complaints declined. (Gentner, Wourms, Hunn, & Farrell, 1996)

Development of an efficient helicopter tool kit.

A striking example of the benefits of HE involvement is the design of the tool kit for helicopter mechanics. Historically, aircraft maintenance tool kits have been large, awkward, and heavy to transport on deployments. Based on HE recommendations, the organizational tool kit for one helicopter was reduced from 134 tools to only 6 tools. This redesign reduced what is usually a trunk-sized kit to a canvas pouch that is approximately half the size of a rolled-up newspaper. (Skelton, 1997)

Antisubmarine Warfare System.

Using mission task and function analysis methods the HE practitioner shaped the design process of this system. The designers were able to meet mission objectives while incorporating many off-the-shelf components, lowering overall system cost. During T&E, the system substantially exceeded customer expectations, and subsequently the design lead to a highly successful deployment. (J. B. Shafer, personal communication, May 7, 1998)

Experimental Helicopter Technological Integration.

During mid-nineteen eighties studies were conducted to determine if a single pilot could perform a scout/attack mission using advanced cockpit technology that previously required two aviators. Function analysis was used to determine which mission segments had the greatest workload, and pilots were interviewed regarding flight deck automation and workloads. Next, pilots were assessed using fixed based simulators installed with a prototype cockpit design. The tests and interviews led to two conclusions: (1) a highly effective pilot orientated cockpit was designed, and (2) although an exceptional single pilot could perform the scout/attack mission, under battle stress the pilot would become overloaded and, consequently, the mission performance would be sacrificed. Due to early HE involvement, the military had the opportunity to discontinue a project before any further investment was required. (J. B. Shafer, personal communication, May 7, 1998)

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